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DEVISING A MULTI-CRITERION APPROACH TO FORMING A PORTFOLIO OF TERRITORIAL COMMUNITY PROJECTS ON THE BASIS OF PUBLIC PARTICIPATION

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This study investigates the process of forming and optimizing the structure of the public participation project portfolio (public budget) of a territorial community given the multi-vector nature of residents' requests and limited resource provision. The results aim to solve the task of ensuring the overall quality and balance in the formation of participatory budgets. This is achieved through the automated selection of innovative and social initiatives that correspond to the specificity and level of their funding.

A method of situational structuring of the public participation project portfolio by categories of thematic areas as sub-portfolios has been devised. Compared to conventional approaches, which are usually based on only one criterion of direct rating voting, the proposed approach is based on multi-criteria selection and situational adaptation of the portfolio architecture. The approach algorithm uses a combination of evaluation of the results of mathematical modeling using non-parametric statistics and the AHP method. This is explained by the fact that the multi-criteria structuring method allows for a better integrated result compared to traditional approaches.

The approach was tested on the basis of a set of real projects in three thematic areas. According to the test results, it was found that the integrated indicator of the socio-strategic effect of the portfolio using the cross-matrix model is 21% higher than when using the conventional rating selection. The efficiency of budget use increased by 11%.

Such results indicate the possibility of effective application of the designed toolset in practice for automating and eliminating subjective factor in the distribution of large arrays of participatory budget funds by local governments

Keywords: set of initiatives, situational structuring, Kruskal-Wallis criterion, rank correlation, AHP method

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1. Introduction

In the context of modern decentralization and the development of a service-oriented state, direct democracy mechanisms are gaining strategic importance for the sustainable development of territories [1]. One of the most effective tools of this type are public participation projects (public budget), the methodology of selection and prioritization of which acts as a powerful innovative mechanism for ensuring strategically oriented socio-economic development [2]. This tool is aimed, first of all, at forming the joint responsibility of local governments and residents for their own well-being. It has significant potential for consolidating resources, increasing the effectiveness of community activities, and contributes to increasing transparency and the level of trust in management decisions made at the local level [3]. Minimizing subjectivity in the process of making such decisions requires the use of sustainable multi-criteria approaches [4, 5], which are simultaneously combined with placemaking methods, improving not only the infrastructure but also increasing the level of social cohesion and trust within the community [6, 7].

The budget of public participation in the classical sense is based on two fundamental principles. First, it is the prerogative of residents to directly determine the directions of distribution of a certain share of budget funds in accordance with the priority needs of the territory. The implementation of such initiatives requires synergy between technical planning standards and the social readiness of the community to accept them [8], and the orientation to the requests of residents directly determines the overall competitiveness and level of trust in local authorities [9]. At the same time, the results of the expression of citizens' will are mandatory for the authorities to implement. Second, this is the cyclical nature of the process – public participation projects are planned for implementation during the budget year, and the initiation and selection procedure itself is repeated annually.

Although it is difficult to determine the exact number of cities that have implemented public budgets, but, according to World Bank experts, their number already exceeds one and a half thousand. It is important to emphasize the universality of this mechanism. The public participation model can be adapted and implemented in structures of any level – from large megacities and united territorial communities to micro districts, educational institutions, and even, under certain conditions, private business organizations. Practice proves that the use of structured decision-making systems significantly increases stakeholder satisfaction [10], but the implementation of such digital projects must take into account the specificity of the local socio-political context [11]. Digitalization itself should serve the strategic goals of sustainable development of the territory [12], taking into account the interconnections and life cycle of projects [13]. This also requires an appropriate institutional framework and the development of digital governance (e-government) tools [14, 15].

Despite significant practical experience, the key issue is the methodological complexity of prioritizing the submitted initiatives [2, 10, 13]. The need to balance the subjective preferences of residents and the objective constraints of municipal management requires devising a specialized multi-criteria approach to forming a balanced portfolio of projects, which determines the purpose of our study.

Thus, the relevance of scientific research within this area is due to the objective necessity of transition from spontaneous selection of local initiatives of residents to scientifically based modeling of processes of formation of municipal portfolios of projects. The modern vector of development of this scientific problem requires devising approaches that make it possible to balance the level of electoral popularity of ideas among the population with strategic goals of development of territories, resource limitations, sectoral proportions, as well as general socio-economic efficiency of created objects.

2. Literature review and problem statement

Study [1] assesses territorial development plans. The authors propose a multi-criteria model that integrates a set of indicators, in particular, such as economy, society, infrastructure, etc., with subjective assessments of stakeholders. In this case, the analytic hierarchy process (AHP) method was used to determine their weights. The result of the study was a system that makes it possible to identify the most critical zones that are priorities for investment, where the social effect will be maximum. The model proposed in [1] is limited by the specificity of "lagging" regions where survival criteria prevail. Because of this, its direct transfer to the tasks of restoration and sustainable development of modern communities is methodologically complicated.

In [2], a new methodology for selecting a project portfolio is described, based on prioritization. The main idea is how to transfer individual preferences into a specific mathematical choice. In this case, multi-criteria decision analysis (MCDA) and stochastic analysis were applied, which makes it possible to deal with situations where the exact weighting coefficients of the criteria are unknown or debatable. As a result, the proposed model helps form a portfolio that is as stable as possible under different financing conditions and different views of experts or the community. The assessment of the applied value of the model [2] indicates the excessive complexity of its initial mathematical setup, which significantly limits the possibility of its widespread use by local managers.

The authors of work [3] investigate the fundamental dilemma of local self-government: why some projects that are liked by the community are not perceived as legal or fair, and vice versa. The study offers a conceptual framework for analyzing how different groups (politicians, administrators, and citizens themselves) evaluate the results of community participation in territorial management. Analysis of the provisions in [3] reveals that it focuses on the political and psychological aspects of the perception of management decisions of local authorities and joint management of the development of territorial communities. The objective mathematical tools for calculating the weights of criteria are left out of the researchers' attention, which makes it impossible to use the work for algorithmic conflict resolution.

In [4], the influence of subjectivity when assigning weight coefficients to criteria when selecting project portfolios was investigated. In this case, an iterative trichotomous approach (ITA) was proposed, which makes it possible not only to select the best projects but also to divide the entire array of ideas into three baskets. First of all, the so-called "reliable" projects are identified, which fall into the portfolio at any weights. Then, "borderline" projects are determined, the fate of which depends on the subjective choice of weights. Rejected or "weak" projects never fall into the portfolio. Multi-criteria mixed integer linear programming was applied in combination with an iterative algorithm. The proposed algorithm allows the decision-maker to see which projects are undisputed leaders according to all criteria and which are controversial. This approach removes the accusation of bias, since the choice is based on mathematical stability, and not on personal sympathy – subjective opinion. Analytical analysis of the model [4] showed that it is adapted to the technical parameters of industrial facilities, while the "soft" social factors of community satisfaction within the framework of the specified approach are mathematically impossible to formalize. For a territorial community, it is more difficult to mathematically describe the "social satisfaction" of residents as accurately as the "probability of technology success". The ITA method also requires powerful computing resources and specialized software.

In [5], a comprehensive review of the current state of multi-criteria analysis methods is provided. The authors offer a clear classification of methods for determining the weights of criteria for decision-making regarding renewable energy systems. The main proposal is the transition to hybrid techniques that combine different methods to increase the accuracy of the choice. The authors analyze and compare the following classical and modern methods: AHP/ANP (for structuring hierarchies); TOPSIS/VIKOR (for determining the proximity to the ideal solution); PROMETHEE/ELECTRE (for pairwise comparison of projects), etc. However, this study is exclusively theoretical in nature, dedicated to the criteria and methods of selecting energy projects. In addition, it does not contain practical proof of the effectiveness of the application of the proposed methods and techniques when forming a community project portfolio.

In [6], the "seesaw effect" in participatory budgeting is studied – a situation when the initial enthusiasm of the community is replaced by disappointment due to delays in the implementation of selected projects. It was found that a successful portfolio of community projects is based not only on the correct mathematical selection, but also on constant communication. Work [6] proves that if there is an agent of change in the community who pushes projects through administrative barriers, the level of public trust remains high even when they are delayed. A critical review of this publication allows us to identify its exclusively sociological vector, which completely eliminates the need to build quantitative mathematical models of prioritization of initiatives. Such specificity is due to the fact that the study does not contain a mathematical description of the prioritization process and considers public participation as a long-term political process, and not as a one-time evaluation event.

In [7], an integrated approach is proposed, in which participatory budgeting is considered not just as a financial tool but as a placemaking method – construction of a high-quality public space. The main idea of the work is that involving citizens in the selection of projects improves not only infrastructure but also social cohesion, the so-called "social capital" of the community. Work [7] proves that the best portfolio of projects is compiled when the community participates not only at the voting stage but also at the stage of joint design. The result is a transition from a list of desired solutions to a structured portfolio of projects that have high aesthetic and functional value for the territory. However, the cited work focuses more on architectural, urban, and social aspects. It lacks a mathematical description of the project prioritization model.

Study [8] provides a systematic review of how energy efficiency could be integrated into urban planning through policy and best practices. The authors highlight successful cases of integrating energy conservation into municipal development strategies implemented in a portfolio of projects. It is proven that success depends on the synergy between technical standards and the social readiness of the community to accept these standards. An expert analysis of the work indicates its isolation on engineering and planning aspects, as a result of which the applied participatory toolkit of residents' influence on the selection of such solutions remains uncertain.

Work [9] investigates factors that make local authorities competitive. They propose using a model of organizational excellence, which is based on seven key criteria: leadership, strategic planning, customer (community) orientation, data analysis, focus on people, operational efficiency, and final results. Researchers analyzed data from Indonesian municipalities to statistically confirm how each element of governance affects the overall competitiveness of the territory. It is proven that strategic planning and community orientation have the greatest impact on competitiveness. This means that communities that involve residents in the formation of their plans (project portfolios) receive better development indicators and a higher level of trust than those that work according to a closed model. Scientific evaluation of the proposed approach allows us to establish that the model is built exclusively on the "top-down" principle, which excludes the possibility of its application for discrete micro structuring of individual local projects submitted by the community.

Study [10] considers the development and implementation of a project prioritization methodology for the municipality of Mecca. The authors propose a structured decision-making system that helps the city authorities select projects under conditions of a limited budget and a large number of requests. The work used the Analytical Hierarchy Process (AHP) method, with the criteria divided into several groups: social impact, economic efficiency, technical feasibility, and strategic compliance with the city's development goals (Vision 2030). A mathematical model was constructed that allows each project to be assigned a numerical rating (scores). Work [10] proves that the use of AHP significantly increases the level of stakeholder satisfaction, as they see the logic of the choice. However, the example of Mecca has a specific religious and tourist context – servicing pilgrims, which requires specific criteria; for other cities and territorial communities, these criteria will need to be adapted to other needs. It can also be concluded that the AHP method can be difficult for direct voting by residents, so it is better to use it at the level of expert groups or community working committees.

In [11], the effectiveness of implementing digital projects at Belgian municipalities was investigated. It was found that "digital governance" is not a universal process – each city interprets it in its own way, depending on the local political context. Work [11] suggests distinguishing between a technocratic approach (focus on technology) and a socio-political approach (focus on changing relations between authorities and citizens). A qualitative study of several smart cities in Belgium was applied. It was found that many "Smart City" projects are actually aimed at internal optimization of the work of the city hall, and not at real expansion of citizens' rights – democratization. The study emphasizes the importance of aligning digital tools with the real needs of the local community. Analysis of the results of study [11] allows us to assert that the authors focused solely on the political interpretation of digitalization, completely ignoring quantitative selection algorithms and mathematical methods for ranking relevant initiatives.

In [12], the SDC (Strategic Digital City) model is described as a tool for managing a set (portfolio) of urban projects. The main idea is that digitalization should not be chaotic; it should serve the strategic goals of sustainable development. Work [12] proposes an architecture where digital services, public administration, and community resources work as a single ecosystem. The study is based on a deductive approach and analysis of several cases of Brazilian municipalities. The authors use qualitative analysis to examine how strategic planning affects the performance of projects in the areas of mobility, security, and ecology. A list of strategic subprojects is compiled, which together form a "Smart City". The authors prove that the success of the portfolio depends on the digital maturity of the municipality and the ability of local authorities to integrate IT solutions into the daily lives of residents. The study of the SDC architecture revealed a complete lack of a formalized mathematical apparatus for direct ranking and selection of digital city projects by residents themselves.

The results of study [13] suggest a portfolio optimization model that takes into account the project life cycle and interactions. The authors argue that conventional portfolio selection models are static, while real projects evolve in stages. The model helps decide which projects to start now and which ones in the following periods to obtain the maximum total effect. Multi-criteria nonlinear programming and an improved genetic algorithm were used to find optimal solutions. The model takes into account three types of interaction: resource, technical, and synergistic, when, for example, two projects together provide more benefit than each separately. Work [13] proves that ignoring interactions between projects leads to inefficient budget allocation. The proposed algorithm makes it possible to balance risks and benefits over the entire planning horizon, but its implementation is mathematically complex. The analysis of this model reveals that due to its high computational and mathematical complexity, it is focused exclusively on deterministic industrial systems. For territorial communities with their "soft" social criteria, it is unsuitable without radical simplification or adaptation through fuzzy sets.

In [14], a significant body of scientific work was analyzed, barriers to e-government implementation were classified, and success factors for local government were synthesized. It was found that without proper institutional framework and staff training, digital tools (e.g., platforms for voting on projects) can exacerbate inequality between active urban centers and passive rural areas. However, the analysis of the aforementioned work reveals that the author focuses purely on a descriptive description of the institutional environment, without proposing any specific algorithm for directly forming a balanced portfolio.

In [15], the evolution of public administration in the era of digital technologies is investigated. The work proposes a Smart Governance model, which is based on the use of data (Data-driven decision making) to increase efficiency, transparency, and citizen engagement. The main focus is on how integrated technological systems help governments make better strategic decisions. It was determined that the key to success is not just the availability of technology but a change in the management paradigm – from a closed bureaucracy to an open ecosystem. The results of the study prove that Smart Governance allows municipalities to better coordinate resources and respond faster to the needs of the public. A study of the provisions of this work revealed that the detailed architecture of smart governance does not contain the main applied element – a specific mathematical algorithm for the operational selection of local projects into the general municipal pool.

The results of study [16] demonstrate what organizational characteristics allow cities to successfully implement digital transformation (Smart City). The work offers a model of organizational capacity, which consists of three dimensions: human capital (staff skills), technical infrastructure, and management processes. The study is based on the experience of three successful European cities. It was found that digital transformation and the involvement of residents in community management are often hampered not by the lack of software but by an outdated organizational culture. It is proven that for the portfolio approach to work, the municipality must invest in staff training and change decision-making procedures. A study of the provisions of this work revealed that the detailed architecture of smart governance does not contain the main applied element – a specific mathematical algorithm for the operational selection of local projects into the general municipal pool.

Paper [17] examines how local governments use financial tools (including bonds) to finance urban development. The authors propose a multi-scalar approach that explains how decisions at the community level are influenced by national financial policies and global capital markets. The study is based on a quantitative analysis of municipal bond issuance data and a qualitative analysis of the regulatory framework. The authors use statistical modeling to track where the funds are spent, and which types of projects are prioritized. They find that the use of financial tools forces local governments to select projects that have a clear investment appeal or high strategic importance. This creates the risk of ignoring small-scale social initiatives in favor of large infrastructure projects that are easier to present to lenders. The scientific analysis of this financing model indicates that the macroeconomic focus of their authors actually eliminates the mechanisms of direct democracy and public participation, shifting the emphasis exclusively to technocratic and commercial interests.

Thus, studies [1–3] emphasize the existing problem of devising approaches to taking into account the priorities of stakeholders and assessing territorial development plans when forming a portfolio of projects. However, there are no comprehensive solutions to this problem. The main focus is either on meeting the basic needs of "lagging" regions without taking into account the goals of sustainable development [1] or is only on the political and psychological aspects of perception and transparency of procedures without providing a specific mathematical algorithm for resolving conflicts of interest [3].

Papers [2, 4] emphasize the need to use multi-criteria analysis and mathematical modeling to ensure the stability of choice and remove subjectivity from decision-makers since ignoring the stability of weighting factors and bias in their assignment can lead to the formation of a suboptimal portfolio of projects [4, 5]. However, the proposed solutions relate mainly to technical, industrial, or research projects, where the criteria are clearly measurable, and do not take into account the "soft" nature of the criteria of social satisfaction of community residents. In addition, these solutions require significant computing resources, specific software [4], or a high level of mathematical training of users [2].

In studies [5–12] concerning the implementation of modern decision-making methods and digitalization tools, there is no convincing evidence for the practical application of the proposed models directly for the formation of a portfolio of projects of territorial communities. Most of these solutions are of an exclusively theoretical nature [5], based on sociological and urban aspects of communication and placemaking without a strict mathematical formalization of the prioritization process [6, 7], focus on engineering and planning standards of energy efficiency [8], or a general assessment of the effectiveness of the municipality "from above" [9]. Even with the implementation of multi-criteria analysis (AHP) systems, they are often oriented to a specific tourist and religious context [10] or are aimed at internal optimization of the work of the city hall, rather than at real democratization and involvement of citizens [11, 12]. In addition, the dynamic nature of the life cycle of projects and synergistic interactions between them are not taken into account [13].

In addition, the criteria for adapting digital governance tools (e-government, Smart Governance) to the conditions of decentralization need additional clarification [14, 15] as the outdated organizational culture of municipalities and low institutional capacity often hinder the actual implementation of such models [16]. It should be noted separately that the use of alternative financial tools (for example, municipal bonds) shifts the focus to large infrastructure facilities, completely ignoring small social initiatives of residents [17]. This creates the problem of balancing diverse (social, technical, economic, and environmental) indicators in a single system [1, 5, 13]. In addition, in the aforementioned studies, the effectiveness of portfolio formation is assessed mainly according to static or purely technocratic criteria, which does not take into account the need to simultaneously ensure transparency, legitimacy in the eyes of the community, and mathematical stability of the final choice.

Thus, there is a task of ensuring the overall quality and balance of the process of forming a portfolio of projects of a territorial community, taking into account the specificity of participatory management. Therefore, there is a need to conduct research into this area to devise a hybrid multi-criteria approach to evaluating and ranking projects, to be solved by combining the subjective priorities of stakeholders with objective indicators of sustainable development of the territory. This will subsequently make it possible, having a limited budget and a large number of requests from residents, to form a sustainable, transparent, and legitimate portfolio of community projects. The results could be used as the basis for an information and analytical system (for example, the Smart Governance platform) of automated decision-making support for local governments.

3. The aim and objectives of the study

The purpose of our study is to devise a scientific and methodological approach to multi-criteria modeling, optimization, and formation of a balanced portfolio of public participation projects in the context of resource scarcity of territorial communities. This will make it possible, taking into account the specificity, financial scale, and industry affiliation of residents' initiatives, to carry out automated selection and prioritization of projects using objective expert and statistical analysis. In practice, this will contribute to increasing the transparency and legitimacy of the distribution of budget funds, ensuring the stability of the portfolio to changes in financing conditions, eliminating sectoral distortions, and maximizing the integrated socio-economic effect of the implementation of projects in the context of participatory management.

To achieve the goal, the following tasks were set:

– to build models of the structure of the portfolio of public participation projects;

– to devise a method of situational structuring of the portfolio of public participation projects and mathematical tools for checking sectoral and financial relationships within the portfolio;

– to carry out experimental testing of the proposed multi-criteria approach using the example of an array of territorial community projects.

4. The study materials and methods

The object of our study is the process of forming and optimizing the structure of the portfolio of public participation projects (public budget) of a territorial community given the multi-vector nature of residents' requests and limited resource provision.

The principal hypothesis assumes that the use of a system of multi-criteria selection and situational structuring of the portfolio, based on the individual preferences of stakeholders, could provide a significant increase in the overall quality, balance, and legitimacy of the final portfolio. Compared to conventional single-criteria approaches, the proposed multi-criteria approach would avoid monopolizing funding for one sector, remove accusations of bias of the authorities, and take into account the strategic goals of community development.

In the process of conducting the study, an assumption was adopted – the main hypothesis can be confirmed if the experimental testing of the designed mathematical tools proves the following. A formed matrix or combined portfolio provides a higher integrated socio-economic effect and resistance to changes in financing conditions than a portfolio formed according to a linear structure.

The main simplification accepted in the study is to limit the time horizon of portfolio planning to a standard annual budget cycle without deep modeling of long-term multi-year lags of facility operation. In addition, in the mathematical model, the optimization of interactions between individual projects was considered as relatively independent at the level of technical implementation. Full accounting of resource and synergistic relationships between all residents' initiatives at the initial stage of decentralized management significantly complicates the algorithm without a significant increase in accuracy for small local projects.

The theoretical basis of our study was formed by scientific work in the field of multi-criteria analysis and investment prioritization [1, 2, 4, 5], conceptual approaches to assessing the social effects of municipal management and participatory governance [3, 6, 7, 9], engineering and planning and digital models of the formation of smart city ecosystems [8, 11, 12, 16], as well as mathematical methods for optimizing complex project portfolios and financial modeling of territorial development [10, 13, 14, 15, 17].

To solve the tasks set in the work, a set of general scientific and special methods was applied, the totality of which forms the methodological basis of the study, namely:

– when processing literary sources, studying the evolution of the problem and the degree of its solution – methods of scientific identification, comparative analysis, as well as the collection, analysis, and systematization of statistical data;

– when developing the concept of forming a portfolio of public participation projects – abstract-logical method and case method;

– when analyzing the factors of portfolio formation and criteria used for evaluating, selecting, and prioritizing initiatives – Spearman and Kendall correlation analysis methods in combination with the case method;

– when devising a method for situational structuring of a set of projects – the concept of situational management, the method of hierarchy analysis (AHP), and the non-parametric criterion (test) of Kruskal-Wallis significance;

– when constructing a mathematical model for determining the optimal portfolio composition under strict constraints – the method of integer (Boolean) linear programming, methods for assessing the effectiveness of investment projects and the concept of the time value of money;

– when formulating final conclusions and scientific and methodological recommendations – the abstract-logical method and the concept of participatory management.

For further testing of the research results and automation of calculations of multi-criteria matrices, specialized software and the Python programming language (The Netherlands) were used with the application of libraries for discrete optimization and statistical analysis.

The devised approach was tested on the example of a formed array of 12 public participation projects with a total cost of 8550000 monetary units within three thematic areas of the territorial community with a total budget limit of 5000000 monetary units. Experimental modeling of portfolio formation using the conventional rating approach and the proposed matrix cross-model using the criteria of the number of votes, strategic relevance (AHP) and budget sustainability confirmed the high efficiency of situational structuring. Based on the calculation of non-parametric Kruskal-Wallis criteria ($p = 0.034$) and Spearman rank correlation ($r_s = 0.95$ for the area of urban development), the need for sectoral and intra-level financial quotas was mathematically substantiated. Comparative analysis of optimization results proved that integration of the methods of hierarchy analysis and integer linear programming makes it possible to automate project selection, prevent sectoral biases and discrimination of small initiatives. At the same time, the total useful effect of the portfolio increased by 21% while the efficiency of budget use increased by 11%, thereby completely eliminating the subjective factor on the part of representatives of local self-government bodies.

5. Results of devising a multi-criteria approach to forming a portfolio of public participation projects

5. 1. Construction of models for the structure of a portfolio of public participation projects

The effective functioning of participatory budgeting tools at the level of territorial communities directly depends on the quality of management processes at all stages of their implementation. Despite the significant potential of public participation projects in strengthening trust between the authorities and society, the practice of their implementation reveals a number of methodological and organizational contradictions. The transformation of residents' initiatives into a balanced portfolio of projects requires overcoming specific barriers that are often ignored by classical project management models.

The identification of key problems in this area is critically important for several reasons. First, it makes it possible to move from intuitive selection of initiatives to systematic architectural design of the portfolio. Second, the delineation of these problems illustrates the points of conflict of interest between the subjective priorities of the community and the objective constraints of the municipality (Fig. 1).

Fig. 1 shows the conceptual triad of basic tasks that arise in the process of managing a set of public budgeting initiatives and defines a logical sequence of problems that require a scientific and methodological solution.

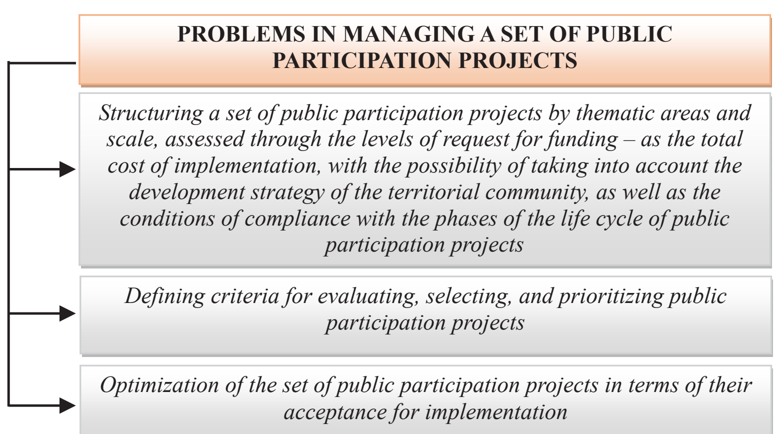

Fig. 1. Problems in managing a set of public participation projects

The first block illustrates the issue of classification and strategic decomposition. The need to structure the set of public participation projects according to two fundamental vectors is substantiated: thematic direction (industry specificity) and scale, which is expressed through the amount of necessary funding (total implementation cost). Particularly important in this context is the requirement for the mandatory integration of these projects into the general strategy for the development of the territorial community, as well as the consideration of time and resource parameters in accordance with the phases of their life cycle. This makes it possible to prevent chaotic financing and ensure a synergistic effect from the implementation of the portfolio.

The second block focuses on the methodological task of evaluation and filtering. The process of portfolio formation requires the development and justification of a clear system of criteria for multi-criteria analysis, selection, and further prioritization of initiatives. The complexity of this stage is the need to transform the social expectations of residents into clear measurable indicators that are at the same time consistent with the technical and economic parameters of municipal management.

The third block states the problem of resource optimization. It reflects the task of mathematical and algorithmic modeling of a set of public participation projects under strict budgetary, time, and institutional constraints. Optimization at the stage of accepting projects for implementation ensures the formation of the most sustainable and balanced portfolio, which brings the greatest social benefit for each invested unit of community funds.

To structure a set of initiatives within participatory budgeting, it is advisable to use a portfolio approach. Depending on the scale of the community, the amount of funding and strategic goals, the management architecture can be built on the basis of different organizational schemes. The following models of the structure of a portfolio of public participation projects can be differentiated by the level of hierarchy and the specificity of grouping:

1. Model 1. Linear-branch structure, which includes categories by thematic areas – subdivisions (Fig. 2).

2. Model 2. Two-vector combined structure, which includes categories by funding – sub-portfolios; categories by subject – subdivisions (Fig. 3).

3. Model 3. Matrix cross-structure, which includes categories by subject – sub-portfolios; categories by funding – lower-level sub-portfolios (Fig. 4).

Model 1 is basic and involves grouping projects solely by their functional and sectoral characteristics (for example, "Education", "Healthcare", "Development", "Sports", "Culture", etc.). In such an architecture, the overall portfolio of public participation projects is divided into subdivisions – thematic categories. All submitted initiatives compete with each other within their thematic areas or within a single general budget request, regardless of the cost of their implementation.

This model is best suited for small territorial communities with a relatively small amount of public budget funding and a small number of submitted projects where there is no need to introduce additional financial restrictions for ideas of different scales. However, there is a significant risk of "washing out" small initiatives by large infrastructure projects that objectively require more funds but can collect a significant number of votes. For example, a major renovation of the school stadium versus the arrangement of a small square. In this case, the total set of all projects submitted and admitted to the evaluation stage is defined as set V

$$V = \{v_1, v_2, ..., v_n\}, \qquad (1)$$

where n is the total number of submitted projects, v_i is the i-th specific public participation project ($i = 1, ..., n$).

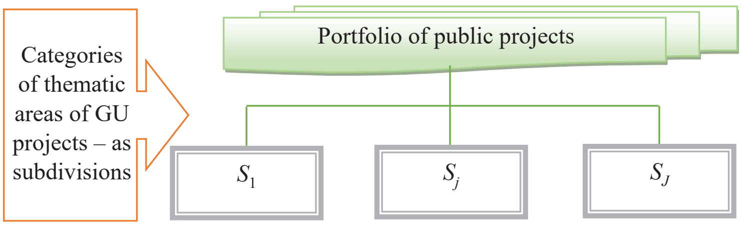

Fig. 2. Model 1 – Linear-branch structure, including categories by thematic areas – divisions

According to the conditions of Model 1, the general portfolio P is structured by thematic directions (industry characteristics) into J subdivisions. The set of subdivisions constitutes the thematic public participation portfolio S

$$S = \{S_1, S_2, ..., S_j, ..., S_J\}, \qquad (2)$$

where S_j is the j-th thematic subdivision of the portfolio ($j = 1, ..., J$).

Each subdivision S_j contains a subset of projects of the corresponding thematic direction

$$S_j = \{v_{1j}, v_{2j}, ..., v_{k_j j}\}, \qquad (3)$$

where k_j is the number of projects related to the j-th thematic area.

The following set-theoretic conditions must be met:

1. The sum of all thematic subdivisions is the total set of submitted projects

$$\bigcup_{j=1}^{J} S_j = V. \qquad (4)$$

2. The same project cannot belong to two different thematic units at the same time. Each project has one clearly defined main theme

$$S_a \bigcap S_b = 0, \forall a \neq b. \qquad (5)$$

3. Each project v_{ij} belongs to the set S_j and is described by a vector of basic characteristics

$$v_{ij} = \langle c_{ij}, e_{ij}, x_{ij} \rangle, \qquad (6)$$

where c_{ij} is the total implementation cost (the amount of required funding) of the i-th project in the j-th subdivision, $c_{ij} > 0$; e_{ij} is an integrated indicator of the effectiveness or priority of the project (stakeholder assessment, number of residents' votes or the result of multi-criteria analysis); x_{ij} is a Boolean (integer) design variable that determines the inclusion of the project in the final portfolio (1 – the project is included in the portfolio, 0 – not).

The final formed portfolio of public participation projects P is a subset of the total set V and can be represented as a combination of selected projects from all thematic subdivisions

$$P = \bigcup_{j=1}^{J} \{v_{ij} \in S_j | x_{ij} = 1\}. \qquad (7)$$

The objective function (optimization criterion) is to maximize the overall social effect (or the total level of community satisfaction) from the implementation of the portfolio

$$F(X) = \sum_{j=1}^{J} \sum_{i=1}^{k_j} e_{ij} \cdot x_{ij} \to \max. \qquad (8)$$

System of restrictions:

1. The total cost of all selected projects from all divisions cannot exceed the amount of funding allocated to the public budget (B)

$$\sum_{j=1}^{J} \sum_{i=1}^{k_j} c_{ij} \cdot x_{ij} \leq B. \qquad (9)$$

2. If the community development strategy requires that no thematic area has a monopoly, maximum restrictions on funding for a separate unit S_j may be introduced

$$B_j^{\min} \leq \sum_{j=1}^{k_j} c_{ij} \cdot x_{ij} \leq B_j^{\max}, \forall j = 1, ..., J, x_{ij} \in \{0,1\}. \qquad (10)$$

Thus, mathematically, Model 1 is reduced to a classical linear integer (Boolean) programming problem – the Knapsack Problem, where subdivisions S_1, ..., S_J serve as a tool for structural accounting, monitoring, and ensuring thematic diversity of community initiatives.

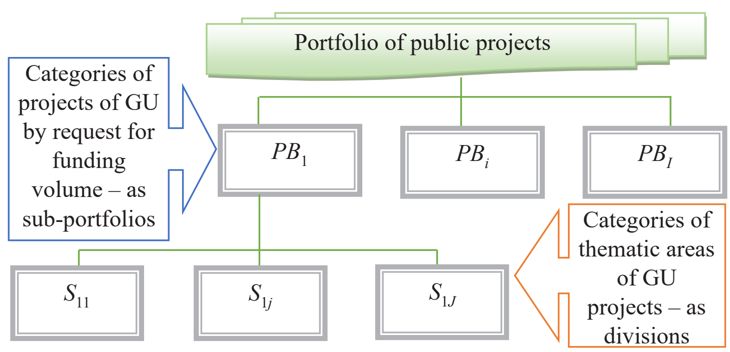

Fig. 3. Model 2 – a two-vector combined structure, including funding categories – sub-portfolios and thematic categories – divisions

Model 2 implements a two-level system of filtering and resource allocation. At the first level of the hierarchy, the entire array of initiatives is divided into sub-portfolios by the amount of funding (usually "Small Projects" and "Large Projects", or "Local" and "Citywide"). At the second level, within each financial sub-portfolio, subdivisions are distinguished by thematic areas. The community's financial resources are pre-quoted (for example, 40% of the budget is allocated to small projects, 60% to large ones). Competition and ranking take place separately within each financial sub-portfolio, and the sectoral division (subdivisions) serves for analytics and strategic monitoring.

This model ensures the protection of the interests of the authors of small local initiatives since they do not compete with capital-intensive projects. The model allows for a balanced distribution of funds, but the distribution of ideas by thematic subdivisions here is mainly informational in nature and does not directly affect the nonlinear programming algorithm during portfolio optimization.

For the mathematical description of Model 2, a two-level hierarchical decomposition is used. At the first level, the total pool of projects is distributed by financial scale into autonomous sub-portfolios, and within each of them there is a division into thematic subdivisions.

The entire array of projects V is classified by the amount of required financing into I sub-portfolios PB

$$V=\{PB_1,PB_2,...,PB_i,...,PB_I\}, \quad (11)$$

where PB_i is the i-th financial sub-portfolio (e.g., PB_1 is small projects, PB_2 is large projects, $I = 2$).

Within each financial sub-portfolio PB_i, projects are differentiated by J thematic areas. Then the subdivision S_{ij} is the set of projects that simultaneously belong to the i-th financial sub-portfolio and the j-th thematic area

$$S_{ij}=\{v_{1ij},v_{2ij},...,v_{k_{ij}ij}\}, \quad (12)$$

where v_{mij} is the m-th specific project ($m = 1, ..., k_{ij}$); k_{ij} is the total number of projects in the j-th thematic subdivision within the i-th financial sub-portfolio.

Each financial sub-portfolio is composed of its thematic subdivisions

$$PB_i=\bigcup_{j=1}^{J}S_{ij}, \forall i=1,...,I. \quad (13)$$

The condition of uniform classification – the project cannot belong to two different sub-portfolios or subdivisions at the same time. Each project v_{mij} belongs to a set S_{ij}, which is described by a set of characteristics

$$v_{mij}=\langle c_{mij},e_{mij},x_{mij}\rangle, \quad (14)$$

where c_{mij} is the amount of financing required to implement the m-th project; e_{mij} is an integrated indicator of the effectiveness or priority of the project; x_{mij} is a Boolean variable for the inclusion of the project in the final portfolio.

The main difference of Model 2 is that the financial resources of the community are allocated between sub-portfolios. The objective function is to maximize the overall social effect. For each financial sub-portfolio PB_i, the total value of the selected projects is maximized

$$F_i(X)=\sum_{j=1}^{J}\sum_{m=1}^{k_{ij}}e_{mij}\cdot x_{mij}\to \max. \quad (15)$$

Or for the entire portfolio as a whole

$$F(X)=\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{k_{ij}}e_{mij}\cdot x_{mij}\to \max. \quad (16)$$

Constraint system:

1. Local budget constraints on sub-portfolios or quotas. The total cost of projects selected within the i-th sub-portfolio cannot exceed quota B_i allocated to it

$$\sum_{j=1}^{J}\sum_{m=1}^{k_{ij}}c_{mij}\cdot x_{mij}\le B_i. \quad (17)$$

2. Global community budget constraint

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{k_{ij}}c_{mij}\cdot x_{mij}\le B. \quad (18)$$

3. Sectoral strategic limits within sub-portfolios can be set optionally. If it is necessary to ensure that within a specific sub-portfolio, for example among small projects, no one area takes all the funds, restrictions are introduced on the S_{ij} subdivisions

$$\sum_{m=1}^{k_{ij}}c_{mij}\cdot x_{mij}\le B_{ij}^{\max}. \quad (19)$$

4. The boundary conditions for the design variables are similar to Model 1.

Mathematically, Model 2 is transformed into a multi-resource knapsack problem or a system of several isolated classical linear integer programming problems. It makes it possible to remove the competition between capital-intensive and local initiatives at the constraint level (B_i), ensuring a fair distribution of funding, where subdivisions S_{11}, ..., S_{IJ} perform the function of matrix control of the sectoral structure of the portfolio.

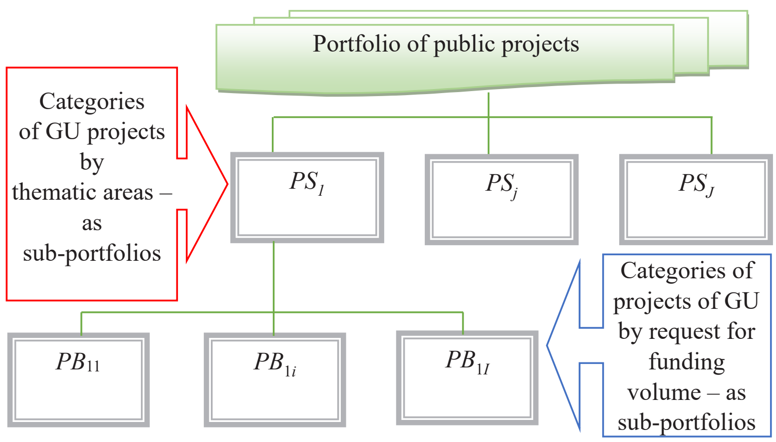

Fig. 4. Model 3 — matrix cross-structure, including thematic categories — sub-portfolios and funding categories — lower-level sub-portfolios

Model 3 is the most complex and hierarchically complex. It is based on the initial division of the overall portfolio into strategic sub-portfolios by thematic areas. In the next step, each such thematic sub-portfolio is decomposed into lower-level internal financial sub-portfolios. For example, such decomposition can be carried out into small/large or short-term/long-term projects within a specific industry.

The community rigidly establishes funding limits for specific strategic goals. For example, the sub-portfolio of environmental projects receives a fixed amount X, the sub-portfolio of digital projects – the amount Y. Then, within the environmental sub-portfolio, the funds are again divided between a pool of small and a pool of large environmental initiatives.

This model is optimal for large cities, megacities, or progressive decentralized communities that implement the concept of Smart Governance, where participatory budgeting is an integrated part of the long-term development strategy of the territory. It makes it possible to achieve maximum compliance of the portfolio with the global goals of sustainable community development and to avoid the situation when, for example, 90% of the winners represent only one area (for example, school improvement). At the same time, the model is mathematically and organizationally the most complex, requiring the development of specialized software to automate multi-criteria analysis and calculate the weights of criteria.

For the mathematical description of Model 3, an inverted two-level decomposition was used where the strategic-industry allocation of resources has the highest priority. At the first level of the hierarchy, the entire array of initiatives is structured by thematic sub-portfolios, and at the second level (within each topic) it is divided into lower-level financial sub-portfolios:

Level 1. Strategic-thematic quota (upper-level sub-portfolios). The entire set of projects V is primarily classified by industry characteristics and thematic directions into J sub-portfolios PS

$$V = \left\{PS_1, PS_2, \ldots, PS_j, \ldots, PS_J\right\}, \tag{20}$$

where PS_j is the j-th strategic-thematic sub-portfolio ($j = 1, \ldots, J$).

Level 2. Differentiation by financial scale (lower-level sub-portfolios). Within each thematic sub-portfolio PS_j, projects are distributed according to the amount of required financing into I lower-level sub-portfolios PB_{ji}

$$PS_j = \left\{PB_{j1}, PB_{j2}, \ldots, PB_{ji}, \ldots, PB_{jI}\right\}, \tag{21}$$

where PB_{ji} is the i-th lower-level financial sub-portfolio within the j-th thematic sub-portfolio ($i = 1, \ldots, I$).

Then the immediate pool of projects within a specific financial thematic group is their set

$$PB_{ji} = \left\{v_{1ji}, v_{2ji}, \ldots, v_{mji}, \ldots, v_{k_{ji}ji}\right\}, \tag{22}$$

where v_{mji} is the m-th specific project ($m = 1, \ldots, k_{ji}$); k_{ji} is the total number of projects that simultaneously correspond to the j-th thematic direction and the i-th financial scale.

Each individual project v_{mji} belongs to the population PB_{ji}, which includes a set of characteristics

$$v_{mji} = \left\langle c_{mji}, e_{mji}, x_{mji}\right\rangle, \tag{23}$$

where c_{mji} is the amount of financing for the m-th project; e_{mji} is an integrated indicator of the effectiveness or priority of the project; x_{mji} is a Boolean variable for making a financing decision.

In Model 3, the total budget of community B, allocated to the public budget, is initially distributed (quoted) between strategic sectoral areas. The objective function is to maximize the integrated socio-strategic effect of the implementation of the entire portfolio of projects of the territorial community

$$F(X) = \sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{m=1}^{k_{ij}} e_{mji} \cdot x_{mji} \to \max. \tag{24}$$

System of restrictions:

1. Restrictions at the level of lower-level financial sub-portfolios (two-level quota). The total cost of selected projects within each financial thematic group cannot exceed the sub-limit allocated for it

$$\sum_{m=1}^{k_{ji}} c_{mji} \cdot x_{mji} \le B_{ji}. \tag{25}$$

2. Strategic constraints at the level of top-level thematic sub-portfolios: Total spending on a particular industry is severely limited by its global quota

$$\sum_{i=1}^{I}\sum_{m=1}^{k_{ji}} c_{mji} \cdot x_{mji} \le B_j. \tag{26}$$

3. Global budget constraint of participatory community budgeting

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{m=1}^{k_{ji}} c_{mji} \cdot x_{mji} \le B. \tag{27}$$

4. The boundary conditions for the design variables are similar to Model 1.

Mathematically, Model 3 is a multi-objective integer linear programming problem. Unlike previous models, it eliminates the situation of portfolio bias towards only one popular area. For example, when residents vote exclusively for urban development, ignoring environmental projects or digitalization. The model ensures precise adherence to the strategic guidelines for community development by imposing a system of cross-budget constraints (B_{ji}) on each financial-thematic group of projects.

5. 2. Method of situational structuring of a portfolio of public participation projects

The methodological basis of the method of situational structuring of a portfolio of projects is a combination of expert assessment using the analytic hierarchy process (AHP) method and the apparatus of non-parametric statistics – the Kruskal-Wallis criterion and the Spearman/Kendall rank correlation. This makes it possible to identify hidden patterns and contradictions in the array of project proposals.

The logic of the practical implementation of the proposed method is formalized in the form of a sequential decision-making support algorithm – a scheme of situational structuring of a portfolio of public participation projects by categories of thematic areas as sub-portfolios (Fig. 5).

This method is intended for making an informed decision on the choice of portfolio architecture, i.e., the use of Models 1, 2, or 3 based on a statistical analysis of the real nature of the data of a specific territorial community.

The devised method is instrumentally implemented in the form of a sequential decision support algorithm, which includes 12 key blocks, structured into three interconnected stages:

Stage I. Macrostructuring of the portfolio and verification of industry differences (Blocks 1–4):

Block 1. Statistical trigger – Kruskal-Wallis criterion. At the initial stage, the scientific hypothesis is tested about the existence of a significant difference between public participation projects in terms of the size of their request for funding depending on the thematic direction. The assumption is based on the fact that the very "nature" of the industry dictates a different level of financial needs. For example, the direction "Infrastructure Improvement" may be too capital-intensive compared to "Cultural Events". The nonparametric Kruskal-Wallis test is used to test the null hypothesis.

Block 2. Branching point I. The result of the significance test is evaluated. It is determined whether the difference between projects in terms of the size of the financial request by industry is statistically significant.

Block 3. Positive vector of macrostructuring – transition to the "Yes" branch. If the difference is significant, the system makes a recommendation: "Recommend considering the possibility of separating sub-portfolios in the portfolio of projects by categories of thematic directions". This is a preparatory stage for the implementation of the comprehensive Model 3.

Block 4. Alternative vector of macrostructuring – transition to the "No" branch. If the Kruskal-Wallis test shows the absence of significant differences, the industry division is recognized as formal. The recommendation is made: "Do not recommend separating sub-portfolios of thematic directions in the portfolio". The algorithm redirects the process to assess the feasibility of isolating purely financial sub-portfolios for the entire array of projects as a whole.

Stage II. Microstructuring and analysis of internal relationships (Blocks 5–10):

In the case of implementing a positive vector (Block 3), the system launches an iterative cycle for each j-th sub-portfolio of the thematic direction in order to determine the need for financial quotas – the separation of small/large projects within the topic.

Block 5. Correlation analysis (Spearman/Kendall coefficients). The hypothesis about the presence of a significant relationship between two variables is tested: the number of votes received in support of the project and the size of its request for funding within a specific j-th thematic sub-portfolio. Nonparametric Spearman or Kendall correlation coefficients are calculated to establish the strength and nature of this relationship.

Block 6. Branching point II. It is determined whether the identified relationship between votes and the cost of projects in the j-th sub-portfolio is statistically significant.

Block 7. Positive microstructuring vector (transition to the "Yes" branch). If the relationship is significant, the recommendation is made: "Recommend considering the conditions for separating project categories by the size of the funding request as lower-level sub-portfolios within a specific j-th sub-portfolio of thematic direction."

Block 8. Criteria coordination. To detail the conditions for separating financial sublimits in Block 7, the Analytical Hierarchy Process (AHP) method is used, which allows community expert board to establish precise weighting factors and limits for dividing projects into "small" and "large".

Block 9. Alternative microstructuring vector – transition to the "No" branch. If there is no connection between cost and popularity, an additional financial sieve within the industry is redundant. The recommendation is made: "Do not recommend separating project categories by the size of the funding request". Projects within this topic will compete end-to-end (transition to Block 10).

Stage III. Generalization and formation of portfolio architecture (Blocks 10–12):

Block 10. Iteration counter: a control block of the cycle that provides a sequential search of all available thematic areas ($j = 1, \ldots, J$).

Block 11. Cycle completion check point. Condition check: "Have all sub-portfolios of thematic areas been considered?" ($j = J$). If negative, the process returns to Block 5 for the next industry. If positive, the algorithm proceeds to the final stage.

Block 12. Final synthesis of results. The "Generalization of recommendations for structuring the portfolio of public participation projects" is carried out. Based on the combination of decisions made in Blocks 2, 6, and 8, the system generates the final topology of the territorial community portfolio, that is, it builds a rigid matrix structure, combined, or leaves the linear model.

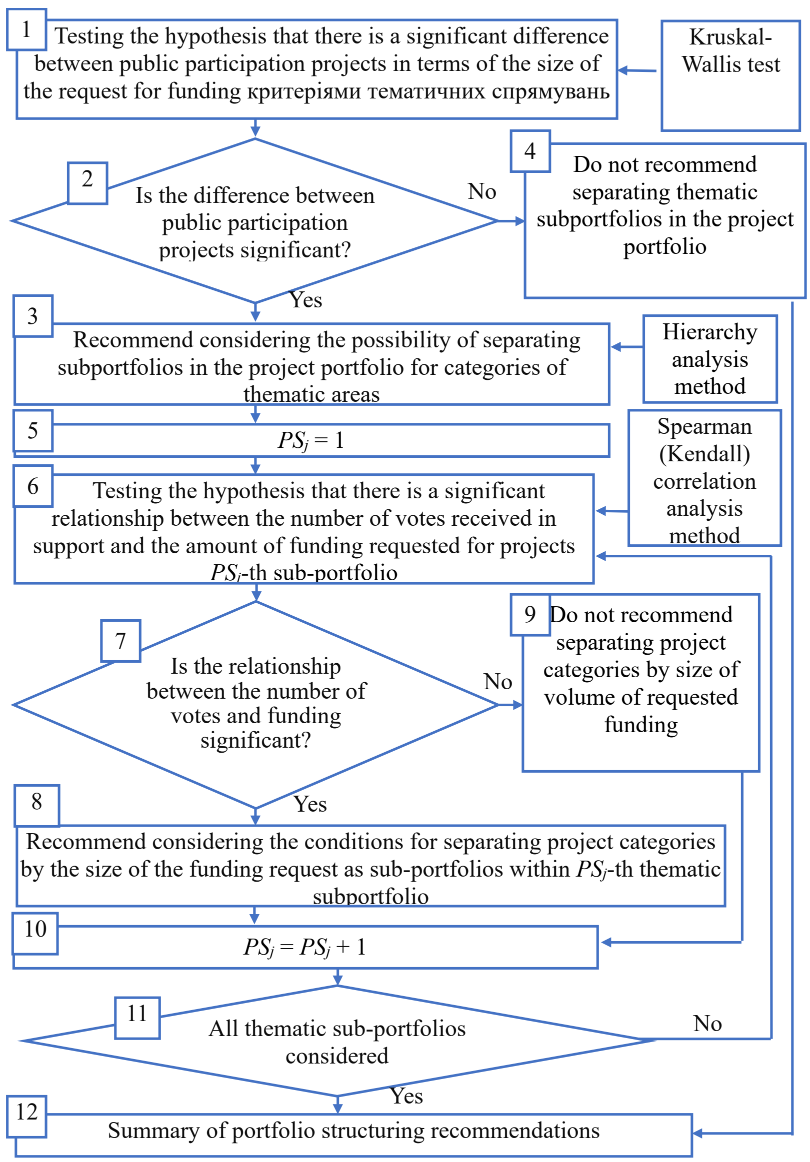

Fig. 5. Scheme of the method of situational structuring of a portfolio of public participation projects by categories of thematic areas as sub-portfolios

The practical value of the proposed scheme is its situational flexibility. Instead of imposing a unified structure on the community, the method makes it possible to analyze the base of submitted ideas using mathematical tools (Kruskal-Wallis, Spearman, Kendall, AHP). This protects the interests of the community. If in a certain year residents submitted projects of the same type in cost, the algorithm will automatically simplify the structure to a linear one (Model 1). However, if a deep imbalance is detected, for example, the housing and communal services sector completely suppresses innovative or social projects, the method will force the system to switch to a matrix structure (Model 3), protecting funds for unprotected thematic areas. Model 2 is activated when the initial Kruskal-Wallis significance test does not reveal significant differences in the budgets of projects in different sectors (Fig. 5, branch "No" in Block 2), which makes sectoral quotas impractical. However, the Analytical Hierarchy Process (AHP) ensures that small projects are protected from large ones at the overall portfolio level.

Given the null hypothesis that the medians of project funding amounts for different thematic areas are the same (H_0), it is necessary to determine the Kruskal-Wallis (KW) criterion

$$KW = \frac{12}{N\left(N+1\right)}\sum_{j=1}^{J}\frac{R_j^{\,2}}{k_j} - 3\left(N+1\right), \qquad (28)$$

where N is the total number of projects in the aggregate; k_j is the number of projects in the j-th thematic direction; R_j is the sum of the ranks of projects in the j-th thematic direction.

If the obtained p-value $p \geq \alpha$ (where α is the accepted significance level, for example, 0.05), then the H_0 hypothesis is not rejected. This means that the industries are financially homogeneous, and division into thematic sub-portfolios of the upper level is not required.

Since the end-to-end division into financial sub-portfolios PB_i is considered appropriate, the threshold values of the project costs for each sub-portfolio are determined using the AHP method (Fig. 5, Block 4).

The expert board builds a matrix of pairwise comparisons of the options for distributing financial boundaries $A = [a_{gh}]$, calculates eigenvectors to determine the weighting coefficients of the boundaries priority w_g and checks the consistency index ($CR \leq 0.1$)

$$A \cdot w = \lambda_{\max} \cdot w \Rightarrow CR = \frac{\lambda_{\max} - n}{\left(n-1\right)\cdot RI}. \qquad (29)$$

Based on the maximum priority w_g, the volume of funding quotas B_i for each sub-portfolio PB_i is determined.

Model 3 is activated if:

1. The Kruskal-Wallis test shows a significant difference ($p < \alpha$) between the budgets of different sectors (Fig. 5, Block 2, branch "Yes"). It is recommended to divide into thematic sub-portfolios of the upper level PS_j.

2. Spearman or Kendall correlation analysis within a specific j-th sub-portfolio reveals a significant relationship between the cost of the project and the number of votes (Fig. 5, Block 6, branch "Yes").

For each thematic sub-portfolio PS_j, the hypothesis about the dependence between the number of votes received (V_{mj}) and the project budget (C_{mj}) was tested using the Spearman rank correlation coefficient

$$r_{S_j} = 1 - \frac{6\sum_{m=1}^{k_j} d_m^2}{k_j \cdot \left(k_j^2 - 1\right)}, \qquad (30)$$

where d_m is the difference between the project's rank by votes and its rank by cost.

The Kendall coefficient is an alternative measure for testing this hypothesis in the case of small samples or overlapping ranks.

$$\tau_j = \frac{C - D}{\frac{1}{2}k_j \cdot \left(k_j - 1\right)}, \qquad (31)$$

where C is the number of matched pairs, D is the number of mismatched pairs.

If for the j-th sub-portfolio the relationship is significant ($p_{corr} < \alpha$ and $r_s > 0.3$), this indicates that large projects "take away" votes from small ones due to their scale. Then, according to the scheme (Fig. 5, Block 7), it is necessary to carry out internal financial quotas – to create sub-portfolios of a lower level PB_{ji}.

For those industries where the correlation turned out to be significant, the AHP method is used in Block 8 (Fig. 5). Experts evaluate the criteria for sustainable development of the territory to determine:

1. The optimal cut-off line between small and large projects within the jth industry.

2. The coefficients of internal distribution of funds α_{ji}. What share of the total budget of the industry should be given to small projects, and what to large ones.

The financial limit for the cross-group is

$$B_{ji} = a_{ji} \cdot B_j. \qquad (32)$$

Thus, the AHP method in this case acts as a precise calibration tool that translates the mathematically justified need for quotas into specific financial constraints (B_i or B_{ji}) for integer linear programming.

5. 3. Testing the multi-criteria approach to forming a portfolio of projects

To demonstrate the practical operation of the devised multi-criteria approach and the method of situational structuring, a conditional example of forming a portfolio of public participation projects for a territorial community was considered. Projects were selected for modeling according to thematic areas typical for local budgets in Ukraine. 5 experts – representatives of local communities of Ukraine – were involved in voting and evaluating projects for the purpose of testing the multi-criteria approach.

At the same time, it was assumed that the total budget allocated for the implementation of public participation projects is $B = 5{,}000{,}000$ monetary units. 12 projects, which belong to three thematic areas, were selected for modeling:

– S_1 – development and infrastructure;
– S_2 – culture and tourism;
– S_3 – digitalization and education.

Table 1 gives initial data: thematic focus, project cost, number of community votes, and integrated expert assessment of strategic relevance (determined using the AHP method on a scale from 0 to 1).

The integrated project priority indicator (e_i) was calculated as the weighted sum of normalized community votes (weight 0.6) and expert assessment (weight 0.4).

According to the constructed scheme of the method (Fig. 5), a sequential test of statistical hypotheses is performed to determine the optimal portfolio model.

The next step is macrostructuring using the Kruskal-Wallis test according to (28). That is, a check is performed to see whether the difference between projects in terms of the size of the financial request (c_i) depending on their thematic direction (S_1, S_2, S_3) is significant. For calculations, the H_0 hypothesis was adopted that the average financial requests between industries are the same. Ranking of project costs by groups, implemented in the Payton environment (USA), revealed a significant difference (p-value = 0.034 < 0.05). Thus, for this example, the null hypothesis is rejected. The nature of the industries significantly affects the cost of projects – landscaping projects are objectively more expensive than cultural projects. According to Block 3 (Fig. 5), it is recommended to separate sub-portfolios in the portfolio by categories of thematic areas. That is, the transition to Model 3 was performed. Strategic quotas were distributed equally between three areas: 1666667.00 monetary units for each sub-portfolio PS_1, PS_2, PS_3.

Microstructuring was performed within each sectoral sub-portfolio to search for a significant relationship between the cost of the project and the number of votes received (Fig. 5, Block 5). The results of calculating the Spearman rank correlation coefficients (r_s) are given in Table 2.

Table 1

Initial data on the set of public participation projects

Project ID (v_i)	Thematic direction (S_j)	Project cost (c_i), monetary units	Number of community votes	Expert assessment (AHP)	Priority indicator (e_i)
v_1	S_1	1 800 000	1250	0.85	0.82
v_2	S_1	1 500 000	980	0.70	0.67
v_3	S_1	400 000	450	0.90	0.53
v_4	S_1	300 000	380	0.65	0.43
v_5	S_2	800 000	600	0.50	0.46
v_6	S_2	700 000	550	0.55	0.45
v_7	S_2	250 000	410	0.80	0.48
v_8	S_2	150 000	320	0.75	0.41
v_9	S_3	1 200 000	850	0.95	0.71
v_{10}	S_3	900 000	710	0.60	0.53
v_{11}	S_3	350 000	500	0.85	0.55
v_{12}	S_3	200 000	390	0.70	0.46
Total	–	8 550 000	7 390	–	–

Table 2

Results of calculating Spearman's intra-industry correlation

Sub-portfolio	Spearman's correlation coefficient (r_s)	p-value	Conclusion on the significance of the relationship	Algorithm solution (Blocks 7–9 of the scheme, Fig. 5)
PS_1 (landscaping)	0.95	0.012	Meaningful sound, strong direct	Recommend financial quotas (division for small/large projects)
PS_2 (culture)	0.80	0.083	The connection is statistically insignificant	Do not reinforce financial sublimits
PS_3 (digitalization)	0.60	0.233	The connection is statistically insignificant	Do not reinforce financial sublimits

For the PS_1 sub-portfolio, where large projects clearly suppress small ones in terms of the number of votes, using the AHP method, the division limit into small/large projects is set at 500,000.00 monetary units and internal quotas are defined: 30% of the industry budget is allocated to small projects (PB_{11} = 500,000.00 monetary units), 70% to large ones (PB_{12} = 1,166,667.00 monetary units).

To determine the final composition of the portfolio, an integer linear programming problem is solved according to two scenarios:

1. The conventional approach, which consists of simple ranking (Model 1). Projects are selected purely by the maximum number of votes (or the e_i indicator) within the total budget of 5 million monetary units, without taking into account industries and scales.

2. A multi-criteria approach is proposed, in particular, the use of matrix Model 3 with quotas according to the developed scheme (Fig. 5). Optimization is carried out taking into account the system of cross-constraints.

The results of the comparative calculation and optimization, carried out using the Python software environment (USA), are given in Table 3.

Table 3

Comparative results of project portfolio formation

ID	Cost, monetary units	Indicator e_i	Traditional approach – rating (Model 1), x_{ij}	Multi-criteria approach (Model 3), x_{mji}	Note on Model 3 selection
v_1	1800000	0.82	1 (included)	0 (rejected)	Exceeds industry quota for large projects PS_1
v_2	1500000	0.67	1 (included)	1 (included)	Fits the criterion of optimization of large projects PS_1
v_3	400000	0.53	0 (rejected)	1 (included)	Included due to the small projects quota PS_1
v_4	300000	0.43	0 (rejected)	0 (rejected)	There was not enough small sublimit in PS_1
v_5	800000	0.46	0 (rejected)	1 (included)	Included within the Culture sector budget (PS_2)
v_6	700000	0.45	0 (rejected)	1 (included)	Included within the Culture sector budget (PS_2)
v_7	250000	0.48	0 (rejected)	0 (rejected)	Budget constraints PS_2
v_8	150 000	0.41	0 (rejected)	0 (rejected)	Budget constraints PS_2
v_9	1200000	0.71	1 (included)	1 (included)	Industry leader in Digitalization (PS_3)
v_{10}	900000	0.53	0 (rejected)	0 (rejected)	Budget constraints PS_3
v_{11}	350000	0.55	0 (rejected)	1 (included)	Included in the balance of the industry quota PS_3
v_{12}	200000	0.46	0 (rejected)	0 (rejected)	There was not enough left in PS_3
Total portfolio costs			4500000 monetary units	3950000 monetary units	Budget efficiency is 11% higher
Total effect (sum e_i)			2.20	2.66	The overall beneficial effect increased by 21%

With the conventional approach, only 3 large projects (v_1, v_2, v_9) were included in the portfolio. The budget was spent only by 4.5 monetary units due to the inability to choose a combination without a financial sieve. In addition, a significant sectoral imbalance arose – 73% of the funding was interested only in the domain of improvement (S_1), and the domain of culture (S_2) did not receive any funding, which can provoke social tension and residents' distrust of the legitimacy of the choice.

According to the proposed multi-criteria approach (Model 3), the system blocked the too expensive project v_1, which allowed us to include a balanced pool of projects (v_2, v_3, v_5, v_6, v_9, v_{11}). The portfolio evenly accommodates all three realms of community life. Thanks to the allocation of a sublimit for small projects in the field of improvement, the local project v_3 received protection, which under the traditional approach would have been completely ignored.

The integrated indicator of the socio-strategic efficiency of the portfolio increased from 2.20 to 2.66 (+21%), and the level of use of the allocated budget approached the maximum value, which fully confirms the working hypothesis of our study.

6. Discussion of results based on testing the method of situational structuring of a portfolio of public participation projects

The identified conceptual triad of basic problems of managing a set of public participation projects (Fig. 1) allowed us to state a multi-criteria optimization problem and construct three basic architectural models of the structure of the municipal portfolio. At the same time, the conventional rating voting, which leads to sectoral distortions, is replaced by a multi-criteria model of integer linear programming where the objective function maximizes the integrated socio-strategic effect under a system of rigid cross-budget constraints. A differentiation of the management architecture according to linear-sector, two-vector combined and matrix cross-principles is proposed (Fig. 2–4). This makes it possible to structure residents' initiatives by thematic direction and scale of financing with mandatory integration into the general strategy for the development of the territory and taking into account the phases of the project life cycle.

The devised method of situational structuring and multi-criteria formation of a portfolio of public participation projects (Fig. 5, (1) to (27)) is based on the mathematical apparatus of optimization and non-parametric statistics. At the same time, the task of modeling the composition of the portfolio of initiatives of residents of territorial communities is reduced to maximizing the overall useful effect under the existing strict cross-constraints (20) to (27). A logical and structural scheme for implementing the method has been proposed (Fig. 5). This allows for the allocation of resources taking into account the specificity, scale, and internal nature of the submitted project proposals. In the future, this will ensure high transparency of the budget process and strategic balance in the development of the territory.

Unlike existing approaches, the proposed method situationally takes into account the structure of actual requests of the current period, avoiding their artificial averaging. In particular, compared to socio-urban and conceptual studies [3, 6, 7], which substantiate the importance of social capital and communications but do not offer calculation tools, the devised method provides a mathematical formalization of the prioritization process. Compared to precise mathematical models [2, 4, 13], which are focused on industrial or research projects with high requirements for computing resources and user qualifications, the proposed approach is adapted to "soft" social criteria of public choice. In addition, unlike municipal management models "from above" [9, 11, 12, 15], which assess the overall effectiveness of city halls or governance architecture, this method allows for discrete selection and ranking of individual local initiatives "from below". This was made possible due to the advantage of the developed approach. It consists in the fact that when justifying the portfolio architecture, a consistent expert and statistical assessment of the data set is carried out according to a set of criteria (28) to (32). In particular, unlike conventional approaches, which do not take into account the relationship between the project budget and its popularity among residents, this study integrates a number of additional tools such as the Kruskal-Wallis criterion (28), Spearman's rank correlation (30), or Kendall's (31), and the Analytical Hierarchy Process (AHP) method (29). Directly due to the application of these criteria in the proposed approach, the conditions of quality, proportionality, and social justice of portfolio formation are satisfied, taking into account the specificity of participatory governance.

The devised approach was tested on a set of 12 public participation projects, four of which are related to the domain of urban development and infrastructure, four to culture and tourism, and four to digitalization and education (Table 1). A statistical analysis of the initial data was conducted. The results of the calculation of the Kruskal-Wallis criterion (p-value = = 0.034 < 0.05) showed that for the taken set of projects, the difference in the size of the financial request between different thematic areas is significant. This confirmed that the "nature" of the industries (in particular, the capital intensity of urban development) dictates a different level of financial needs, which makes it advisable to separate thematic sub-portfolios of the upper level according to the matrix cross-structure (Model 3).

In addition, according to the results of testing using the Spearman coefficient, it was found that within the "Landscaping" sub-portfolio there is a strong significant relationship between the cost of the project and the number of community votes ($r_s = 0.95$, $p = 0.012$). This confirmed the effect of suppressing small projects by large ones since larger infrastructure facilities objectively accumulate greater interest from residents. Thanks to the application of the Analytical Hierarchy Process (AHP) method, the dividing line between small and large projects (500,000 monetary units) was successfully justified and internal financial quotas were introduced (30% for small, 70% for large projects).

Comparative modeling using the conventional rating method and the constructed Model 3 confirmed the high effectiveness of the proposed algorithm-scheme (Table 3). The conventional approach led to sectoral bias (culture received 0% of funding) and the crowding out of small initiatives. In contrast, the multi-criteria approach allowed for the formation of a balanced pool of projects from all sectors. The value of the total useful effect of the portfolio (sum e_i) for the proposed model turned out to be 21% higher than with traditional rating selection. In addition, the efficiency of using the total allocated budget (5,000,000 monetary units) when using the matrix model with cross-quotation was 11% higher compared to the vote-based approach.

Thus, the results obtained during our study could in the future become a significant component of information and analytical systems of municipal management and digital platforms of the public budget. On the basis of objectively structured data, a transparent initial basis is formed for making management decisions regarding the implementation or rejection of projects, which minimizes corruption risks and bias of the authorities.

The scope of application of our results is municipal management, processes of strategic planning of local development, and the functioning of digital platforms of participatory budgeting. Mandatory conditions for the application of the devised method are the presence of a significant budget deficit when the total financial request of the submitted initiatives exceeds the financing capabilities of the community. In addition, this method will be more effective if the submitted projects are previously divided into at least three different thematic (sectoral) areas.

The limitation of the proposed approach is that when forming the cross-quotation matrix at the microstructuring stage, only static financial parameters of the current budget year are taken into account. The disadvantage of the devised approach is that at this stage the model considers projects as technical and resource-independent elements. That is, potential synergistic effects, when the implementation of one project reinforces another, or spatial conflicts between infrastructure facilities, are not taken into account.

This shortcoming could be taken into account at the next stage of our study – when designing a comprehensive information and analytical system for managing municipal project portfolios based on geoinformation modeling of territories and dynamic accounting of multi-year lags of facility operation. In addition, in further studies, the base of non-parametric criteria might be expanded for analyzing specific types of data distribution in large communities.

7. Conclusions

1. A multi-criteria problem of optimizing the composition of the public participation project portfolio has been stated; models of the project portfolio structure were constructed. For this purpose, modern approaches to portfolio management in the municipal sector were analyzed and the specificity of participatory budgeting were studied taking into account the interests of different stakeholder groups. It was determined that the conventional approach, based purely on direct rating voting, leads to significant sectoral distortions and discrimination of small local initiatives. Three basic architectural models of the portfolio structure were substantiated: linear-sectoral (Model 1), two-vector combined by the amount of funding (Model 2), and matrix cross (Model 3). The problem of optimizing the portfolio composition was reduced to a multi-criteria model of integer linear programming where the objective function maximizes the integrated socio-strategic effect under a system of rigid cross-budget constraints.

2. A method for situational structuring of a portfolio of public participation projects and a mathematical toolkit for checking sectoral and financial relationships within the portfolio have been devised. The method is based on a logical-structural scheme of 12 consecutive blocks, which allows for flexible adaptation of the portfolio topology to the nature of real data of a specific budget cycle. The mathematical toolkit contains a non-parametric statistical apparatus for objective analysis. The Kruskal-Wallis criterion is used as a macro-filter to check the significance of differences in financial requests between different sectors. The Spearman (Kendall) rank correlation is applied as a micro-locator to identify the relationship between the cost of projects and the number of votes received within each domain. For cases where a significant relationship is identified, the Analytical Hierarchy Process (AHP) method has been integrated, which provides a mathematically justified calibration of internal financial sublimits (quotas) for small and large projects, thereby eliminating the manifestation of subjectivity.

3. An experimental verification of the devised multi-criteria approach and mathematical models of cross-structuring was carried out using an example of an array of territorial community projects. Testing was carried out on a database of 12 public participation projects in three thematic areas (improvement, culture, digitalization) with a total cost of 8,550,000 monetary units at a budget limit of 5,000,000 monetary units. Oue calculation of the Kruskal-Wallis criterion ($p = 0.034$) and Spearman coefficient ($r_s = 0.95$ for the improvement sector) confirmed the need to transition from a simple rating to the proposed matrix Model 3 with the allocation of internal quotas (30% for small and 70% for large projects). Optimization modeling proved that the proposed approach made it possible to prevent sectoral imbalances, protect small social initiatives, and ensure an increase in the total useful effect of the portfolio by 21% compared to the conventional rating, while simultaneously increasing the efficiency of budget funds utilization by 11%. The designed toolkit could serve as an effective means of automating and ensuring transparency of decision-making in local governments.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors legitimately used Gemini (developed by Google) to check grammar, spelling, punctuation, without changing the text, and to search for sources by keywords using the criterion "publications in the last 5 years". The verification of the sources found in this way was carried out by direct access and processing by the authors. The authors assure that the use of this tool did not affect the final conclusions of the study.

Authors' contributions

Tatiana Vorkut: Supervision, Project administration, Conceptualization, Methodology, Investigation; **Vitalii Kharuta**: Methodology, Formal analysis, Validation; **Anna Kharchenko**:

Investigation, Data Curation, Writing – original draft, Software, Project administration; **Yurii Lushchai**: Data Curation, Formal analysis; **Yuliia Bozhok**: Writing – review & editing, Visualization; **Yuliia Artemchuk**: Investigation, Resources.

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