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ORIGINAL

A decision support model for selecting community development projects based on fuzzy logic

Un modelo de apoyo a la toma de decisiones para la selección de proyectos de desarrollo comunitario basado en lógica difusa

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ABSTRACT

The article proposes an approach to selecting a priority public project for financing in the context of a limited budget and lack of unanimity among community residents. Based on the results of an expert survey, a fuzzy decision-making model was built that considers three key variables: the amount that the community is willing to invest, the expected utility of each project, and the decision on the feasibility of increasing or decreasing funding. The Mamdani fuzzy inference system in the MATLAB environment was used to implement the model. Nine basic rules were formed based on linguistic assessments and the results were defuzzied. To build an analytical model of the system's behavior, the method of full rotatable design of the second-order experiment was used, which allowed obtaining a quadratic regression dependence of the output variable on the logarithm of the project cost. The voting results showed the absence of a clear leader among the projects, which further substantiates the feasibility of using the proposed approach. The decision to select the optimal project was made based on minimizing the absolute value of the variable Y, which reflects the degree of deviation from the financial balance. The proposed tool is relevant for the processes of decentralization and development of local self-government, as it allows for formalizing decision-making in situations of limited resources and competition between alternatives.

Keywords: Fuzzy Logic; Decision Support Systems; Public Project Selection; Mamdani Inference; Community Budgeting; Local Governance.

RESUMEN

El artículo propone un enfoque para seleccionar un proyecto público prioritario para su financiamiento frente a un presupuesto limitado y la falta de unanimidad entre los residentes de la comunidad. Con base en los resultados de la encuesta a expertos, se construyó un modelo de toma de decisiones difuso que toma en cuenta tres variables clave: el monto que la comunidad está dispuesta a invertir, la utilidad esperada de cada proyecto y la decisión de aumentar o disminuir el financiamiento. Para implementar el modelo se utilizó el sistema de inferencia difusa Mamdani en el entorno MATLAB. Se formaron nueve reglas básicas basadas en evaluaciones lingüísticas y los resultados fueron defuzzificados. Para construir un modelo analítico del comportamiento del sistema se utilizó el método de diseño experimental de segundo orden completamente rotatorio, el cual permitió obtener una regresión cuadrática de la dependencia de la variable de salida con el logaritmo del costo del proyecto. Los resultados de la votación mostraron la ausencia de un líder claro entre los proyectos, lo que confirma aún más la viabilidad de utilizar el enfoque propuesto. La decisión de elegir el proyecto óptimo se tomó con base en minimizar el valor absoluto de la variable Y, que refleja el grado de desviación del equilibrio financiero. La herramienta propuesta es relevante para los procesos de descentralización y desarrollo del autogobierno local, ya que permite formalizar la toma de decisiones en situaciones de recursos limitados y competencia entre alternativas.

Palabras clave: Lógica Difusa; Sistemas de Apoyo a la Toma de Decisiones; Selección de Proyectos Públicos; Inferencia Mamdani; Presupuesto Comunitario; Gobernanza Local.

INTRODUCTION

Modern territorial communities in Ukraine often face limited budget resources, which complicates the adoption of effective economic decisions. The distribution of funding between important social and infrastructure projects requires consideration of both economic factors and subjective preferences of citizens. In such conditions, classical deterministic optimization methods are not flexible enough, since they do not take into account uncertainty, vagueness and the emotional component inherent in social choice.[1,2,3]

One of the effective approaches to modelling decision-making processes under uncertainty is the use of fuzzy logic. Fuzzy logic is usually employed to handle the concept of partial truth, when truth value may be a real number.[4,5] Mamdani fuzzy inference allows to translate a set of linguistic control rules, which are, in our case, judgements of community activists, into a system of fuzzy logic sets.[6] This approach allows to formalize expert judgments, transform qualitative assessments into quantitative values and take into account vagueness in the formulation of needs and criteria. In combination with economic and mathematical modelling and regression analysis methods, fuzzy logic creates the basis for building adaptive decision- making support systems in a socio-economic context.

The purpose of this paper is to develop and empirically test a model of economic decision- making based on fuzzy logic methods. The model is built taking into account limited funding, the degree of utility of projects and the level of community acceptance of the proposed solutions. As an example of the application of the model, the case of the Zhydychiv territorial community is considered, where the feasibility of financing specific social projects was substantiated based on a survey of residents, cost analytics and software modelling in the MATLAB environment.

The proposed methodology has the potential to be scaled to other communities and local governments, where it is necessary to make complex multi-criteria decisions in conditions of lack of resources and high social responsibility.

METHOD

The study used a combined approach that combines expert assessment, fuzzy logic, and second-order regression analysis methods.

At the first stage, a survey of active community representatives was conducted to identify priorities in spending budget funds. Respondents were offered a list of potential development projects, among which they had to choose one that they considered the most appropriate for implementation. Also, within the framework of the survey, respondents determined what amount they considered "too limited" and "excessive" for the implementation of projects. The data obtained were used to construct membership functions of fuzzy sets. Three fuzzy variables were constructed:

A. X_1 — the amount that the community is willing to allocate for improvement measures.
B. X_2 — the utility of a specific measure (calculated as the natural logarithm of its cost).
C. Y — the decision: to spend a larger or smaller amount.

Membership functions for variables X_1 and Y were constructed based on respondents' ratings, and for X_2 — by logarithmic normalization. For fuzzy sets, Gaussian membership function was used. The reasoning behind this decision is grounded in several theoretical dispositions. Gaussian function is proven to perform well in describing distribution of various polls results.[7] In conditions of uncertainty, when expert assessments are aggregated, it is often assumed that these assessments are normally distributed around the most probable value. The Gaussian membership function naturally reflects this assumption by modelling the degree of truth as a function of deviation from the mean.[8] Moreover, it makes sense to consider the adequacy of project budgets as a normally distributed variable, given the uncertainty inherent in project budgets and the nonlinear change in budget adequacy as its size changes, taking into account the possibility of changes in the scope of project work and changes in the balance of resources used in the project, which equally allow the achievement of commonly defined goals.[9]

Fuzzy inference was performed in MATLAB environment using Mamdani method. A rule base was formed that combines the values of variables X_1 and X_2 to form a recommendation for changing financing Y. Defuzzification results for different combinations of X_1 and X_2 were used as a training sample. Centroid defuzzification method was used.

To construct the analytical model, a full second-order rotatable experimental design was applied. The response surface obtained as a result of fuzzy modelling has a pronounced nonlinear, curvilinear character. A linear model (first order) is not capable of approximating such a complex surface. A second-order model, which includes quadratic terms, allows this curvature to be modelled correctly and extremes to be found, which is key to determining the optimal solution. The experimental design was developed to estimate the coefficients of a second-order polynomial, which includes linear terms, quadratic terms, and terms reflecting the interaction between factors. The complete design ensures that all these effects can be calculated independently of each other, which ensures the completeness and accuracy of the resulting mathematical model. Rotatability ensures the same prediction accuracy of the model for all points equidistant from the center of the experiment (point (0,0) in coded variables). This means that the quality of the model does not depend on the direction of movement from the center, but only on the distance to it. Variable coding was used for normalization, which consists in establishing a correspondence between the actual values of the factors and the coded levels of the rotatable experimental design ($-\alpha$, -1, 0, +1, $+\alpha$, where $\alpha \approx 1,414$). The coding procedure for each factor was carried out as follows: The minimum and maximum values of each variable from the studied range were taken as the extreme points of the range corresponding to the "star" points of the plan $-\alpha$ and $+\alpha$. The central point corresponding to the coded level 0 was calculated as the arithmetic mean of these extreme values. Other key levels of the plan (+1 and -1) were calculated using linear scaling relative to the central point and the full range of values.

The design included 9 experimental points, comprising the center point, factorial points, and star (axial) points. For each of them, the value of Y was manually determined using the fuzzy inference system in MATLAB. The resulting 9 triples (X_1, X_2, Y) became the basis for estimating the parameters of the quadratic regression model.

The significance of the model parameters was tested using the Student's t-test, the adequacy was tested using the Fisher's F-test and the coefficient of determination (R^2). To select the most compromise project, the criterion of minimizing the modulus of the variable Y was applied, which allows determining the option that is as close as possible to the neutral solution.

DEVELOPMENT

The situation in the Zhydychiv community of Lutsk district of Volyn region was considered. The problems of the community are bad roads between villages, the lack of a cultural center (park, club, cafe), an unrepaired school, a kindergarten, and the lack of a full-fledged hospital. The head of the territorial community asked the district leadership and enterprises located in the community for material and financial assistance to solve these problems. As a result, he managed to attract UAH 452 250 from various sources. The solution to the lack of funds was to involve representatives of the Zhydychiv community in the implementation of the work on the terms of voluntary unpaid participation. It was considered that the cost of 1 hour of time was determined[1], as the amount of the estimated salary divided by the labor rate per month with a 40-hour work week: 10 628,39 UAH / 166,17 man-hours = 63,96 UAH/man-hour.

Community representatives (activists) were surveyed about their spending priorities. To check for a statistically significant leader among the projects, a x^2-test of consistency was applied. The overall distribution of votes showed significant variation (CV ≈ 42 %), and the x^2 value indicated a statistically uneven distribution of preferences ($p < 0,05$). However, when analysing only the upper quartile (projects with the largest number of votes), the significance level was not reached ($p \approx 0,61$), indicating the absence of a clear favourite even among the leaders. This confirms the feasibility of using a fuzzy model that allows considering not only the number of votes, but also the usefulness of projects and the perception of financial feasibility. Costs of development projects and votes distribution among survey participants are shown in table 1.

To define the fuzzy concept X1, you must first find the range of possible values of the amounts. This range was taken from table 1: 57 700 UAH – 1 530 450 UAH. Therefore, the middle of the range will be the average of these numbers – 794,075 UAH. In general, each fuzzy variable has three options for its values, which are described by the concepts "Insufficient", "Acceptable" and "Too much". From this figure 1 it follows that some points have already been determined by us. These are T1 = 57 700 UAH, T7 = 1 530 450 UAH and T4 = 794 075 UAH.

Table 1. Estimated cost of work, including materials, voting results for development projects

№	Project	Costs, UAH	Number of votes	% of votes
1.	Road repair, 2,5 km	1 530 450	28	19,72
2.	Club repair	390 400	20	14,08
3.	Kindergarten repair	280 000	15	10,56
4.	School repair	373 200	25	17,61
5.	Park arrangement	57 700	14	9,86
6.	Hospital premises repair	440 800	32	22,54
7.	Store extension to cafeteria	57 700	8	5,63

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To determine the remaining points of the fuzzy sets, a survey of activists from the rural community was conducted. They were initially asked to choose an amount that, in their opinion, lies between insufficient and sufficient funding. A total of 54 people participated in the survey. Among 54 respondents, there were 6 of management personnel, 17 trade workers and teachers, 24 combine harvesters and tractor drivers, 7 livestock farm workers. The distribution of respondents by age group was as follows: 18-25 years old – 11, 25-45 years old – 39, 45-60 years old – 17, over 60 years old – 4.

The graph of the membership function for the concept "Insufficient" is presented in figure 2. It shows that the membership measure of 0,5 corresponds to the amount of UAH 153 000. This amount corresponds to point T2, which should be to the left of point T3.

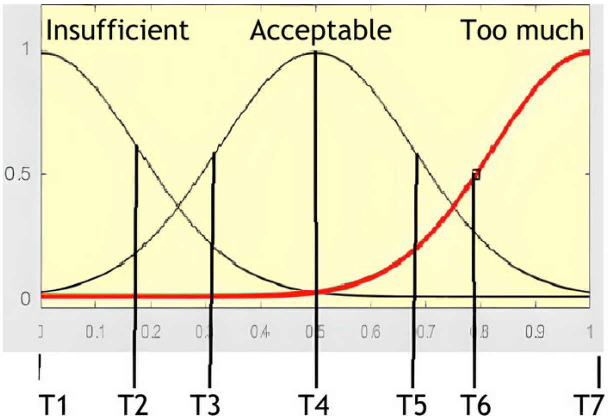

Figure 1. Key points of the numerical characteristic of a fuzzy variable

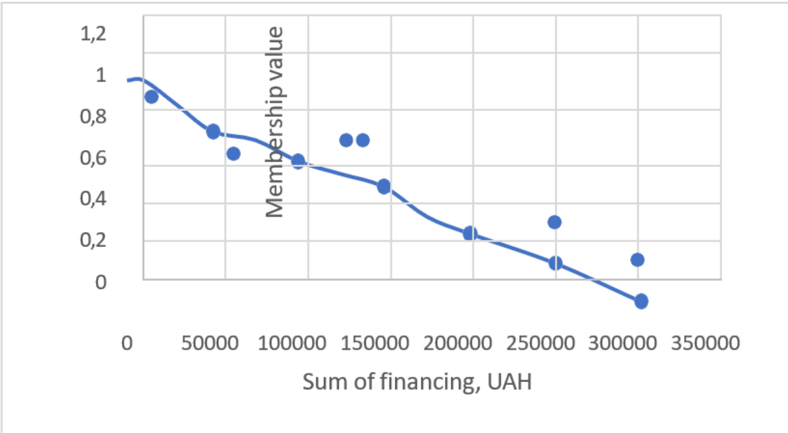

Figure 2. Membership measure of the fuzzy variable "Insufficient"

Activists were similarly surveyed regarding the concept of "Too Much". Additionally, they were explained that the lack of funds would have to be covered by their own labor at the rate of 63,96 UAH/man-hour.

The survey results are presented in figure 3, from which it can be seen that the amount of 790 000 UAH corresponds to point T6, which corresponds to a degree of membership of 0,5, which proves that this point should be to the right of point T5.

Using the MatLab software package, a fuzzy variable X1 was set up - the amount that society can allocate for measures to improve life. The results are presented in figure 4. It can be seen from it that point T6 is located to the left of point T5.

The definition of the fuzzy variable X2 was done by analogy with the definition of X1. But the community activists were unable to find the utility of the introduced amounts. Then it was decided to define the utility of the amount as its natural logarithm, since in most cases researchers describe the utility with just such a function[2].

Then, the values of the corresponding points will be as follows: T1 = Ln (57700) = 10,96301, T2 = Ln (153000) = 11,93819, T3 = Ln (548617) = 13,21516, T5 = Ln (1039533) = 13,85428, T6 = Ln (790000) = 13,57979, T7 = Ln (1530450) = 14,24107. For point T4, which is the center, it is necessary to find the average of points T1 and T7, T4 = (10,96301 + 14,24107)/2 = 12,60204. The decision function – to spend more or less amount Y – is built on the basis of the previous survey, presented in figure 2-3. It can be seen from it that only two graphs need to be taken as the determining graphs: "Take more" – the left graph, and "Take less" – the right graph. The central symmetric graph is not needed in this case.

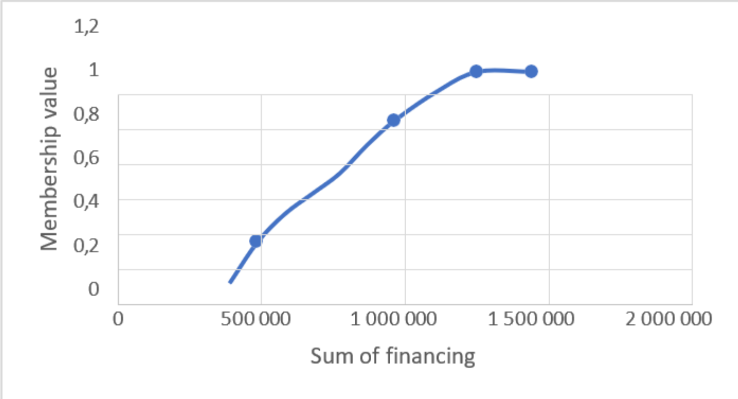

Figure 3. Membership measure of the fuzzy variable “Too much”

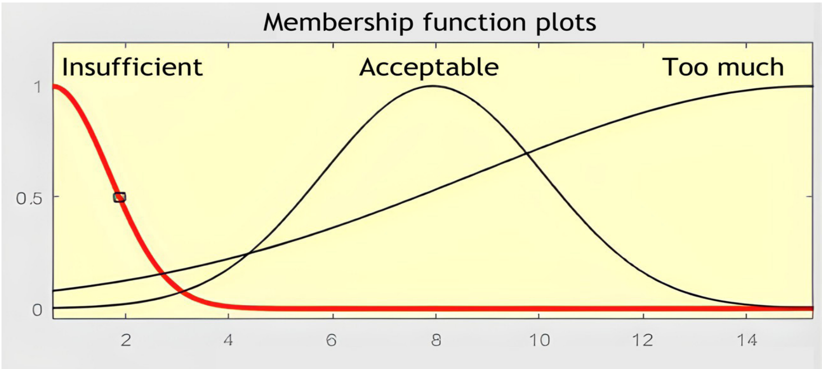

Figure 4. Representation of the fuzzy variable X1 in the MatLab software package (the X axis shows amounts in hundreds of thousands of hryvnias)

The value of the function Y ranges from -1 to +1. If the function takes on negative values, then you need to choose a more expensive project, and if positive, a cheaper one. Obviously, the project whose function is closer in modulus to zero has every chance of being chosen.

On the horizontal axis, it is necessary to set the values from -1 to +1. And the characteristic points (as in figure 1) T2 and T6 should be taken proportionally to the points for the axis of the fuzzy variable X1.

For the point T2, which will be in the negative part of the graph, we will find its position for the fuzzy variable Y, as a fraction of the midpoint T4

T_2=-153000/(794075-153000)=-0,238661623.

Similarly, for point T6, which will be in the positive part of the graph, we find as:

T_6=790000/(1530450-794075)-1=0,07282295.

In order for the fuzzy inference system to start functioning, it is necessary to form a rule base of the form:

IF X1 = A1 AND X2 = A2 THEN Y=B

Where:
X1 and X2 are the input fuzzy variables.
Y is the output fuzzy variable.
A1, A2, B are the corresponding linguistic values.

This study used the Mamdani fuzzy inference method implemented in MATLAB. In particular, associated combinations of values of fuzzy variables X1 (funding amount) and X2 (project utility) with corresponding linguistic estimates of variable Y (budget change decision).

The number of fuzzy rules is defined as the product of the number of terms of each of the input variables. Since each variable has three linguistic values (e.g., “insufficient”, “acceptable”, “too much” for X1), the total number of rules is 3×3=9.

The fuzzy rule base used in this study consists of nine rules that link the input variables "Amount of Funding" and "Project Utility" to the output variable "Decision". These rules were formulated using the Mamdani inference method and are presented below:

1. If the amount of funding is Insufficient and the utility is Low, then the decision is to Increase Funding.
2. If the amount of funding is Acceptable and the utility is Low, then the decision is to Increase Funding.
3. If the amount of funding is Too Much and the utility is Low, then the decision is to Decrease Funding.
4. If the amount of funding is Insufficient and the utility is Acceptable, then the decision is to Decrease Funding.
5. If the amount of funding is Acceptable and the utility is Acceptable, then the decision is to Increase Funding.
6. If the amount of funding is Too Much and the utility is Acceptable, then the decision is to Decrease Funding.
7. If the amount of funding is Insufficient and the utility is High, then the decision is to Increase Funding.
8. If the amount of funding is Acceptable and the utility is High, then the decision is to Increase Funding.
9. If the amount of funding is Too Much and the utility is High, then the decision is to Decrease Funding.

The response surface of the collected fuzzy rules, presented in figure 5, has a nonlinear nature and can be described by second-order polynomials.

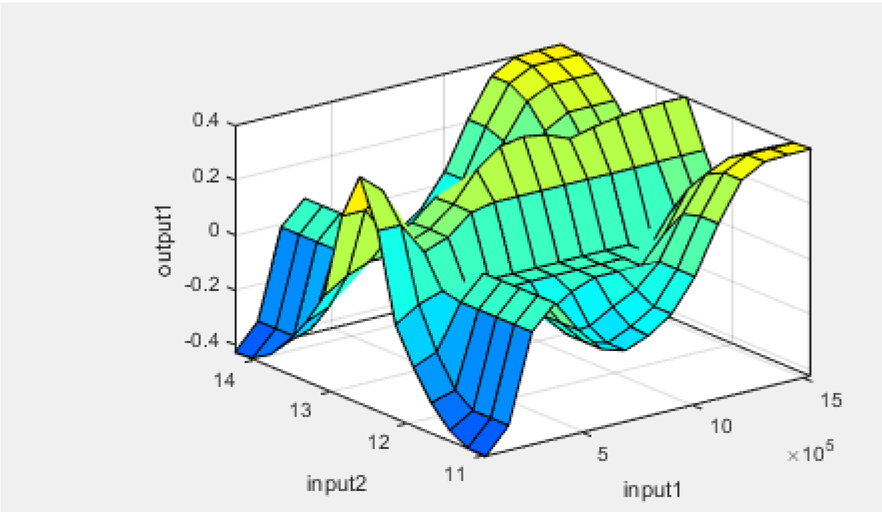

Figure 5. Response surface of given fuzzy rules

It is obvious that it is inconvenient to define a clear conclusion through the MatLab program window. It is better to describe the function of the fuzzy conclusion, as in figure 5, by a second- order polynomial. To do this, we will use the experimental design method, which allows us to reduce the required number of experimental points to a minimum. This plan allows us to describe the experiment by a response function of the form:

$Y = a0 + a1X1 + a2X2 + a12X1X2 + a11X1^2 + a22X2^2$, (4)

To construct the analytical approximation of the fuzzy system's behavior, a full rotatable second-order experimental design was applied. The plan included nine experimental points, combining factorial, axial (star), and central configurations. These points were defined in terms of normalized (coded) values of the two input variables: X1 (amount of funding) and X2 (utility of the project).

The factorial part consisted of four points with coordinates: (+1, +1), (-1, +1), (+1, -1), and (-1, -1).

The axial (star) points extended beyond the factorial square along each axis and included: (-1,414, 0), (+1,414, 0), (0, -1,414), and (0, +1,414), where 1,414 corresponds to √2, ensuring rotatability of the design.

The central point (0, 0) was added to evaluate the model curvature and improve estimation precision.

This experimental layout enabled the evaluation of both linear and quadratic effects of the variables on the output Y, supporting the construction of a second-order regression model that approximates the behavior of the fuzzy inference system.

Based on the triplets of variable values obtained as a result of the full rotatable design of the second-order experiment, the regression model parameters were estimated. To check the quality of the model, Student's criterion were used to determine the statistical significance of individual coefficients, Fisher's criterion to assess the adequacy of the model as a whole, and the coefficient of determination (R^2) to assess the explanatory power of the constructed function.

Taking into account the close relationship between the variables X1 (amount of funding) and X2 (logarithmic utility estimate), the model was transformed to depend on only one variable - the project amount.

For each of the alternative community projects, the value of the output variable Y was calculated. The project for which the value |Y| was the smallest is interpreted as the most balanced, that is, one that does not require budget adjustment.

RESULTS

For nine control points determined according to the plan of the full rotatable experiment, fuzzification, fuzzy response calculation and defuzzification of the results were carried out. The obtained values of the variable Y became the basis for constructing a second-order quadratic regression model. The main goal of building a regression model was to approximate a complex, nonlinear response surface (figure 5) generated by a fuzzy inference system with a simpler analytical function. Thus, the second-order polynomial acts as a convenient "mathematical substitute" for practical calculations. The overall adequacy of the resulting model was assessed using Fisher's criterion (F-test). The result of the analysis shows that the calculated value of the criterion is F(5, 3) = 2,09, where 5 is the number of degrees of freedom for regression and 3 is for residuals. The coefficient of determination R^2 = 0,78 indicates that the obtained model explains 78 % of the variation in the output variable. It should be noted that, given the specific purpose (approximation to simplify calculations) and the limited data set (9 experimental points), full validation of the model on a separate test set or using cross-validation was not performed. The assessment of the risk of overfitting is beyond the scope of this study, which is its methodological limitation.

The significance of each individual coefficient of the regression model was assessed using the Student's t-test. Analysis of p-values showed that none of the coefficients are statistically significant at the generally accepted level of α=0,10. However, the coefficients for the free term (p = 0,111), factor X_2 (p = 0,109), and quadratic term X_2^2 (p = 0,109) demonstrate marginal significance. Given the exploratory nature of the study, these variables were retained in the final model as having the greatest impact on the result.

After simplification, the model was reduced to the dependence of the variable Y on the logarithm of the project cost. An adequate model with statistically significant coefficients has the form:

$$y = -34{,}84 + 5{,}54759697X2 - 0{,}2199568655X2$$

If we assume that the parameter X2 is the logarithm of the sum (S) of the life improvement measure, then finally formula (5) can be represented as

$$y = -34{,}84 + 5{,}54759697LnS - 0{,}2199568655(LnS)^2$$

As part of the analysis, the Y value was calculated for each of the seven projects. In particular:

- Renovation of the hospital premises: Y = 0,106; 32 votes; cost — 440 800 UAH (97 % of the budget)
- Renovation of the road, 2,5 km: Y = 0,446; 28 votes; cost — 1 530 450 UAH (339 % of the budget)
- Renovation of the school: Y = 0,128; 25 votes; cost — 373 200 UAH (83 % of the budget)
- Renovation of the club: Y = 0,123; 20 votes; cost — 390 400 UAH (86 % of the budget)
- Renovation of the kindergarten: Y = 0,137; 15 votes; cost — 280 000 UAH (62 % of the budget)
- Arrangement of the square: Y = -0,459; 14 votes; cost — 57 700 UAH (13 % of the budget)
- Refurbishment of the shop to a cafeteria: Y = -1,020; 8 votes; cost — 30 200 UAH (7 % of the budget)

The smallest absolute value of the variable Y was obtained for the project of renovation of the premises for a hospital (Y ≈ 0,106), which indicates the highest compliance of the requested cost with both public expectations and the available budget. This project also received the largest number of votes — 32, or 22,54 % of the total number of respondent

At the same time, the road repair, which ranked second in terms of votes (28), demonstrated a value of Y = 0,446, which indicates a significant discrepancy between the expected feasibility and the actual cost.

The project of converting a shop into a cafeteria, despite its relatively low cost (110 000 UAH), received the fewest votes (8 people, or 5,63 %) and the value of Y = -1,020 — the most negative among all options. This indicates that, although the project is affordable, it is considered not useful enough and is not a priority for the community.

Thus, the model allows us to identify not only leaders in terms of support, but also their compliance with the allowable budget. As a result, the optimal project for implementation was the project of renovating a hospital building — the only option that simultaneously received the largest number of votes, demonstrated the best agreement with the constructed response function, and fit into the available budget of 452 250 UAH.

DISCUSSION

The results obtained confirm the effectiveness of applying fuzzy logic to solve the problem of choosing a financing project in conditions of social uncertainty and a limited budget. Unlike direct voting, which often demonstrates ambiguous or conflicting priorities, the developed model allows considering not only the number of votes, but also the subjective assessment of utility and perception of permissible costs.

Analysis of the voting results showed the absence of a clear leader among the options (x^2- test, p = 0,61 for leaders), which makes it impossible to use only quantitative indicators in decision-making. In this case, the application of a model based on fuzzy sets allows finding a compromise solution that balances the desired cost and the expected effect of the project implementation.

A feature of the proposed model is that the optimization is carried out according to the criterion of a fuzzy variable Y, which reflects the "signal" to a change in the amount of financing. Thus, the minimum $|Y|$ means achieving a balance — a situation where community needs, perceived value, and expected benefits are aligned without the need for budget adjustments.

The practical value of this approach is that it can be adapted to other contexts where decisions need to be made with the participation of several subjective factors, in decentralization processes, local budget management, or participatory planning.

However, the model has certain limitations: in particular, the dependence of the results on the form of the membership functions and the subjectivity of the surveys that form them. Further research could be aimed at automating the formation of rules and using fuzzy logic in combination with multi-criteria methods.

Another benefit of the proposed approach is its ability to provide a more convincing and transparent rationale for decision-making, especially for community members, compared to simple voting results, which were not perceived as a true consensus.

Furthermore, it is crucial to acknowledge the broader methodological limitations of this study to contextualize its findings. The research is structured as a single-case application, focusing solely on the Zhydychyn community, which restricts the direct generalizability of the specific outcomes to other regions. Additionally, the membership functions, which are central to the model, were constructed based on a survey of a limited sample of 54 activists from a total community population of 4,567. While an expert-based approach is common in fuzzy modeling, this small sample size introduces a potential bias and means the functions may not fully capture the collective preferences of the entire populace. These factors, alongside the inherent subjectivity in choosing the function types, underscore that while the proposed methodology is transferable, the specific model and its results are highly context-dependent.

CONCLUSIONS

The paper proposes an approach to decision-making on financing community projects based on fuzzy logic. Three fuzzy variables were constructed: the amount of financing, the utility of the project, and the decision to change it. Membership functions were determined based on a survey of respondents.

The Mamdani system allowed us to formalize the logic of project selection in the form of fuzzy rules. To obtain an analytical model, a full rotatable experimental design was used, based on which a quadratic regression of the variable Y was constructed. Optimization was carried out according to the criterion of the initial fuzzy variable Y, which reflects the need to increase or decrease the amount of financing. The project for which the value of Y is closest to zero is interpreted as the most balanced option — one that does not require budget correction — and is considered optimal within the framework of making a decision on financing only one project.

The developed tool allows us to formalize the decision-making process in the field of choosing public initiatives, which is especially relevant in conditions of limited financial resources and the absence of a single vision of priorities among community activists. The results of the study have practical value for countries implementing decentralization policies and supporting the development of local self-government.

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