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Use of fuzzy sets in calculating the passenger capacity utilisation rate in conditions where it is impossible to collect objective data

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Abstract. The tasks of planning the organisation of passenger transportation by urban transport in modern Ukrainian conditions face new challenges, in particular, with the complexity or even impossibility of obtaining accurate input data for calculations. The research focused on solving the problem of unavailability of accurate and up-to-date data for calculating the organisation of passenger transportation by urban transport by using fuzzy logic methods. It is assumed that in conditions of limited time for conducting field research or the impact of military operations that cause dynamic changes in passenger traffic through migration processes and allow obtaining data by traditional methods, the proposed approach will allow performing calculations with minimal error. On the example of the coefficient of passenger capacity utilisation on the stage of a transport route, which directly depends on the indicator of passenger occupancy, the possibility of expanding the mathematical model of passenger transportation in urban transport using fuzzy logic approaches is considered. In particular, this refers to replacing input values with a subjective assessment of an outsider in the form of using fuzzy sets. The theoretical study showed the possibility and expediency of using fuzzy sets to solve the problem of the lack of objective input data in calculating the passenger capacity utilisation rate. The general principles of forming universes of fuzzy sets when they are used in mathematical models of the organisation of passenger transportation in urban transport to level the subjectivity of input data are determined. The requirements for the degree of overlap of the accumulated functions of belonging of fuzzy sets of the permissible level of subdivision are described, which can be used to reduce the error of calculations and, accordingly, the dimension of universes of fuzzy sets. The dependence of the tensor bit depth of the initial results on the quantitative indicator of stages on the public transport route, which can be used as a basis for analysing the complexity of calculations, is determined. The general principles of working with fuzzy sets in this mathematical model are shown using the example of calculating the passenger capacity utilisation rate. The study can be useful for city administrations, transport companies, software developers, transport logistics experts, and scientists to optimise public transport operations in the face of a lack of objective data and dynamic changes

Keywords: public transport; organisation of transport routes; passenger capacity of transport; fuzzy logic; tensor

Introduction

The issue of calculating the organisation of passenger transportation on urban transport in Ukraine has become relevant due to the high level of urbanisation and priority focus on improving the efficiency and convenience of public transport, ensuring its superiority over private, in the development and modernisation of transport infrastructure in cities. However, the realities of war have created new challenges for the scientific and transport

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community. Temporary changes in transport routes, changes in the population in areas of cities and in cities in general associated with both continuous shelling of Ukrainian cities (damage to infrastructure) and changes on the line of combat collision (evacuation of the population in frontline cities, return of the population to de-occupied cities) require an immediate response and adaptation of the transport system, which is not possible when using classical mathematical models that provide for the collection of data on passenger traffic by statistical methods and methods of field research, which is complicated, limited in time, and sometimes even impossible (for example, planning when returning the administration to just de-occupied city). It is in such cases that the expansion of existing mathematical models for organising passenger transportation in urban transport using fuzzy logic methods allows calculations based on subjective data with minimal error.

The solution of such problems is quite relevant in modern scientific discourse. In particular, it may be advisable to use Bayesian methods. However, according to P.I. Bidyuk *et al.* (2021), despite all the flexibility in modelling, these methods have significant disadvantages that make it impossible to use them to solve the problem at hand. The choice of model structure and calculation methods requires highly qualified specialists, and the quality of results largely depends on the correct choice of the a priori distribution.

T.W. Richardson *et al.* (2020) propose a missing data imputation method that combines normalising flows and Monte Carlo methods. According to the above data, the use of normalising streams allows accurately estimating the data distribution density, which contributes to better imputation of missing values. But at the same time, the performance of MCFlow algorithms may depend on the choice of hyperparameters, which requires additional experiments to optimise, which is a long process.

A large number of studies note the effectiveness of using fuzzy logic methods to solve problems of the absence of objective input data. R. Saatchi (2024) provides an overview of current developments in fuzzy logic and, in particular, fuzzy inference systems (FIS). The paper discusses the prospects for further development of fuzzy logic, in particular, in industrial processes. Methods of fuzzy logic are widely used in applied fields and in situations involving the presence of various kinds of uncertainties, when these uncertainties cannot be clearly formalised using methods of probability theory and mathematical statistics. Such uncertainties can be caused by the inability to mathematically clearly determine the values of parameters and the boundaries of their belonging, or by incompleteness of needs or uncertainty in the question of the impossibility of the occurrence of certain events.

Studies of the use of fuzzy logic methods in areas related to transport and traffic are becoming increasingly widespread. For example, V. Naumov *et al*. (2021) proposes a methodology for estimating passenger preferences when choosing a bus route in a public transport system, using a mathematical apparatus of fuzzy logic based on a number of subjective characteristics such as: delivery speed, comfort, cost, etc. The originality of the study lies in the application of fuzzy logic to model the subjective preferences of passengers, which allows considering uncertainty and variability in the choice of transport route. As a further development of approaches to replacing missing or fuzzy data, their replacement with linguistic variables is used. For example, a model was developed that evaluates infrastructure projects in road and rail transport, considering the criteria for sustainable development and quality of life. Using the fuzzy logic toolbox package in MATLAB, the authors not only created a knowledge base with linguistic variables, membership functions, and inference rules, but also tested the model on real projects, which confirmed its effectiveness in supporting decision-making (Kaczorek & Jacyna, 2022).

There are a number of studies describing the use of fuzzy logic for mathematical modelling of transport processes. Thus, for example, I. Medvediev *et al.* (2024) developed a mathematical model that allows assessing and managing risks in the conditions of uncertainty typical of modern agribusiness. The study focused on risks in the logistics route of grain transportation from Ukraine to Poland and allows considering subjective and objective risk factors, ensuring adaptation to changing supply chain conditions. X. Yang *et al*. (2022) developed a model that combines various criteria such as comfort, reliability, and accessibility to provide a comprehensive assessment of the operation of the transport system, using fuzzy logic to account for subjective and objective indicators.

Most of the previous studies combine the use of fuzzy logic to level out the absence, fuzziness, or subjectivity of input data. Understanding this allows expanding the searching for literature beyond the specialised topics of transport technologies and use research, approaches and developments in the field of applying fuzzy logic in solving problems from various scientific and applied fields. For example, J. Grosset *et al*. (2024) clearly describe the extended possibilities of using fuzzy logic to solve the input uncertainty problem. In particular, the influence and possibility of mathematical modelling of the process is revealed not only in conditions of fuzzy knowledge (fuzzy sets, linguistic variables, fuzzy decision rules), but also in conditions of fuzzy behaviour (fuzzy conclusions) and fuzzy interaction or roles. The effectiveness of using linguistic variables in solving a decision-making problem under a fuzzy model is shown in a study conducted for an automatic mail sorting line (Grebennik & Kovalenko, 2024). The researchers not only identified input and output linguistic variables, but also substantiated the importance of phasification and dephasisation when using complex multi-tertiary classification systems.

The series of books "Studies in Fuzziness and Soft Computing" edited by J. Katzpshik of Springer Nature Switzerland AG became a fundamental work in the field of studying, researching and describing methods, approaches and implementations of fuzzy logic in various fields of science and technology. It includes publications on various topics in soft computing that cover fuzzy sets, rough sets, neural networks, evolutionary computing, probabilistic and provable thinking, multi-valued logic, and related fields. One of the books in the series under the authorship of T. Bhatia *et al*. (2023) describes a set of methods for finding solutions of the "more-for-less" type for various types of fuzzy transport planning problems. The book presents new methods for solving various types of problems, including symmetric balanced fuzzy transport planning problems, symmetric intuitive fuzzy transport planning problems with mixed constraints, and symmetric intuitive fuzzy linear fractional transport planning problems with mixed constraints. The book discusses in detail their applications using examples of representative tasks and discusses possible areas for further research.

Based on the above, it becomes clear that the problem of the impossibility of obtaining objective data for calculations exists in various fields of science and technology. When solving such problems, they rely on fuzzy logic methods, which demonstrate high efficiency. However, methods of involving fuzzy logic in each individual model are highly variable and require in-depth analysis and research to identify the optimal method for improving the existing mathematical model. The purpose of this study was to evaluate the feasibility of using fuzzy sets to calculate the passenger capacity utilisation rate in conditions of impossibility of obtaining objective data, as well as to determine promising directions for further research to improve the mathematical model of passenger transportation organisation in urban transport.

Materials and Methods

The main stages of the study included the analysis of modern methods of work, such as the Bayesian method, the Monte Carlo method, and fuzzy logic methods, in conditions of inability to obtain objective input data, and the determination of the indicative component (variable) of the mathematical model for the study of passenger transportation in urban transport. Such a component is most susceptible to the influence of fuzziness, and therefore, the consideration of methods of working with it is the most revealing. This allowed investigating and presenting approaches to the use of fuzzy logic methods in a mathematical model, developing an algorithm for working with data that have limited accuracy, and providing recommendations for the optimal choice of parameters for practical implementation of the model.

Calculating the organisation of passenger transportation in urban transport is a complex complex multi-criteria mathematical model that considers a large number of different factors. By comparative analysis of the mathematical models considered by V.V. Bilichenko *et al*. (2020), R.A. Khabutdinov & I.O. Fedorenko (2021), J. Hellekes & C. Winkler (2022), describing the organisation of passenger transportation on public transport, the passenger capacity utilisation rate on the stage as a key component of most models were identified and selected. In addition, in comparison with other indicators such as the average length of the stage, the density of traffic flow, the specific number of traffic lights on the route, it can contain up to 100% uncertainty throughout the route, based on setting the task conditions, since it is based on the filling indicator. The static passenger capacity utilisation rate on the stage was calculated using the equation:

$$\gamma_{ck} = \frac{F_k}{n_{rot} \cdot q_{avg}}, \qquad (1)$$

where F_k – filling on k-th stage; n_{rot} – number of rotations performed by vehicles during peak hours and per day; q_{avg} – average passenger capacity of buses operating on this route. At the same time:

$$F_k = F_{k-1} + P_k - O_k, \qquad (2)$$

where F_{k-1} – filling on the previous k-th stage (on the first stage, this value is zero); P_k and O_k – accordingly, the number of passengers who got on and off the bus at the bus stop.

To investigate the possibility and feasibility of using methods of fuzzy modelling and parameter phasing, the method of parameter modelling and the method of gradual approximation with theoretical verification were used to assess the stability of the model, optimise parameters and estimate the complexity of calculations. To provide a deeper analysis, membership functions were used to describe the uncertainty and variability in the transport models. In the study, universes of possible values of key parameters were created that consider the uncertainty of input data and allow adapting the model to the real conditions of urban transport functioning. The sensitive analysis method was used to determine the quantitative indicator of the complexity of calculations of an improved mathematical model. The calculations were based on the example of the passenger capacity utilisation rate on a transport stage.

Results and Discussion

If it is impossible to obtain up-to-date accurate data of filling parameters, they can be obtained as a subjective assessment of the observer in the form of a linguistic variable, or a fuzzy set. To calculate the passenger capacity utilisation rate based on a subjective estimate of the number of passengers who entered or left the vehicle at a stop, at least 3 fuzzy sets must be defined: few ($\tilde{A}$), many ($\tilde{B}$), full/all ($\tilde{C}$). For a conditional fleet of vehicles, where q_{avg} = 18 persons the corresponding universes can acquire the following values:

$$\cup_A = \{1, 2, 3, 4, 5, 6, 7, 8\};$$
$$\cup_B = \{7, 8, 9, 10, 11, 12, 13, 14, 15, 16\};$$
$$\cup_C = \{15, 16, 17, 18\}.$$

Therefore, there will be corresponding fuzzy sets that can be represented as follows:

$$\tilde{A} = \{a,\ \mu_A(a) \mid a \in \cup_A\};$$
$$\tilde{B} = \{a,\ \mu_B(a) \mid a \in \cup_B\};$$
$$\tilde{C} = \{a,\ \mu_C(a) \mid a \in \cup_C\}.$$

For a better understanding of the distribution of universes of the proposed fuzzy sets, they are shown in the graph of membership functions (Fig. 1) as an example. The X-axis represents the number of passengers who entered the vehicle according to the subjective assessment of the observer (variable *a*), while the Y-axis shows the value of the membership function of the corresponding fuzzy set µ.

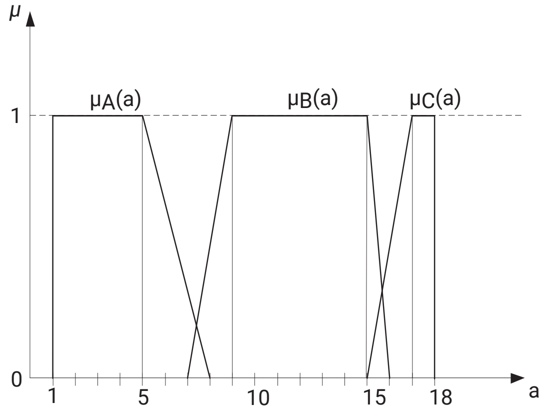

Figure 1. Graphs of functions belonging to fuzzy sets $\tilde{A}$ (little), $\tilde{B}$ (many) and $\tilde{C}$ (full)
Source: developed by the author based on the proposed as an example of fuzzy sets and their universes

In conditions of independent calculations (i.e., the absence of recursive use of previously computed data), such an approach would be optimal for solving the problem of input data fuzziness. However, when calculating the passenger capacity utilisation rate on a particular stage (equation 1), the fill indicator is used F_k (equation 2), which is directly dependent on the calculated filling rate in the previous stage (F_{k-1}).

For clarity, the value of the fullness indicator is substituted into the equation for calculating the passenger capacity utilisation rate on the stage, and the calculation problem is formulated at the initial stages of the route. For example, according to the subjective assessment of an outside observer, "few" passengers entered the bus at the starting point of the route, then the calculation of the passenger capacity utilisation rate on the 0-th stage will look like this:

$$\gamma_{c0} = \frac{P_0}{n_{rot} \cdot q_{abg}} = \frac{\{1,2,3,4,5,6,7,8\}}{n_{rot} \cdot q_{avg}}, \qquad (3)$$

which does not cause any special difficulties, even with manual calculation and after calculation, it will represent a certain set of values . Let on the next stage, according to the observer's assessment – "many" went in and "few" came out. In this case, the equation statement will be as follows:

$$\gamma_{c1} = \frac{F_0 + P_1 - B_1}{n_{rot} \cdot q_{avg}} =$$
$$= \frac{\{1,2,3,4,5,6,7,8\} + \{7,8,9,10,11,12,13,14,15,16\} - \{1,2,3,4,5,6,7,8\}}{n_{rot} \cdot q_{avg}}. \qquad (4)$$

Even at this stage, there is actually a transition to a 3-dimensional tensor of results , which directly depends on the conditional three-dimensional tensor of the fullness coefficient represented by a combination of fuzzy sets . Even at this iteration of calculations, the need to automate such calculations is clearly seen. Each subsequent iteration of calculations, each subsequent stage on a public transport route, will add a bit depth to the measurement of the fullness indicator and, as a result, the passenger capacity utilisation rate itself. On a conditional *k*-th stage, the problem of finding the passenger capacity utilisation rate takes the following form (if you entered – "few", left – "many" on the stage *k-1* and went in – "few", went out – "all" on the *k*-th stage):

$$\gamma_{ck} = \frac{\begin{Bmatrix} \{F_{k-2}\}\tilde{A}_1\tilde{B}_1 & \{F_{k-2}\}\tilde{A}_1\tilde{B}_2 & \cdots & \{F_{k-2}\}\tilde{A}_1\tilde{B}_n \\ \{F_{k-2}\}\tilde{A}_2\tilde{B}_1 & \{F_{k-2}\}\tilde{A}_2\tilde{B}_2 & \cdots & \{F_{k-2}\}\tilde{A}_2\tilde{B}_n \\ \cdots & \cdots & \ddots & \cdots \\ \{F_{k-2}\}\tilde{A}_n\tilde{B}_1 & \{F_{k-2}\}\tilde{A}_n\tilde{B}_2 & \cdots & \{F_{k-2}\}\tilde{A}_n\tilde{B}_n \end{Bmatrix} + \tilde{A} - \tilde{C}}{n_{rot} \cdot q_{avg}}, \qquad (5)$$

where the tensor dimension digit will be in the following dependence on the ordinal (quantitative) stage indicator:

$$n = k + (k - 1) + 2 = 2k + 1. \qquad (6)$$

That is, for example, the tensor will be 23-dimensional, which, in fact, leads such calculations to the field of "Big Data". However, there are several other factors that increase the complexity of the mathematical model. Returning to the consideration of graphs of functions belonging to fuzzy sets (Fig. 1), which were adopted to solve the problem of fuzzy input data to solve the problem of determining the passenger capacity utilisation rate, it is possible to clearly distinguish the coverage area of possible values of fuzzy data sets after accumulating their membership functions (Fig. 2), or rather zones of non-belonging, in which, in particular, some possible values of universes do not even reach a probability of 0.5.

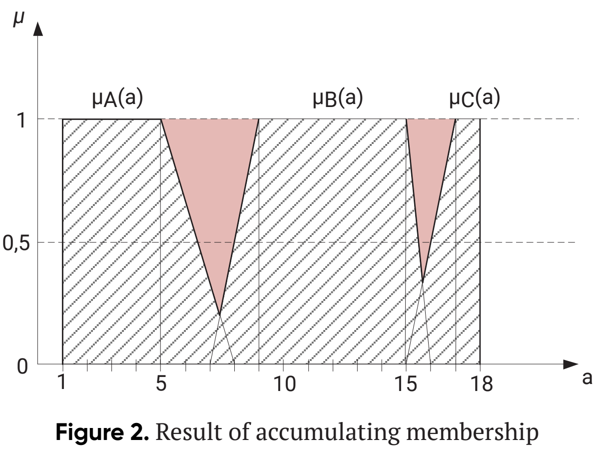

Figure 2. Result of accumulating membership functions of fuzzy sets
Note: $\tilde{A}$ (little), $\tilde{B}$ (many) and $\tilde{C}$ (full)
Source: compiled by the author based on Figure 1

Figure 2 shows that the selected fuzzy sets, or rather their universes, are not sufficient to solve the problem with a sufficient level of reliability. Since it is not appropriate to increase the coverage of universes and thereby expand the boundaries of sets, this disadvantage, which has a negative impact on the accuracy of calculations, must be solved by subdividing. This results in a larger set of fuzzy sets with a more complex function for accumulating membership functions, but with a much smaller calculation error. For example:

$$\tilde{A} = \{a, \mu_A(a) \mid a \in \{1, 2, 3, 4, 5\}\};$$
$$\tilde{B} = \{a, \mu_B(a) \mid a \in \{4, 5, 6, 7, 8\}\};$$
$$\tilde{C} = \{a, \mu_C(\mathrm{a}) \mid a \in 7, 8, 9, 10, 11\}\};$$
$$\tilde{D} = \{a, \mu_A(\mathrm{a}) \mid a \in \{10, 11, 12, 13, 14\}\};$$
$$\tilde{E} = \{a, \mu_B(\mathrm{a}) \mid a \in \{13, 14, 15, 16, 17\}\};$$
$$\tilde{F} = \{a, \mu_C(\mathrm{a}) \mid a \in \{16, 17, 18\}\}.$$

It is predicted that the proposed level of subdivision of fuzzy set universes will increase the minimum allowable probability level to 0.5. Figure 3 shows graphs of the membership functions of the proposed fuzzy sets.

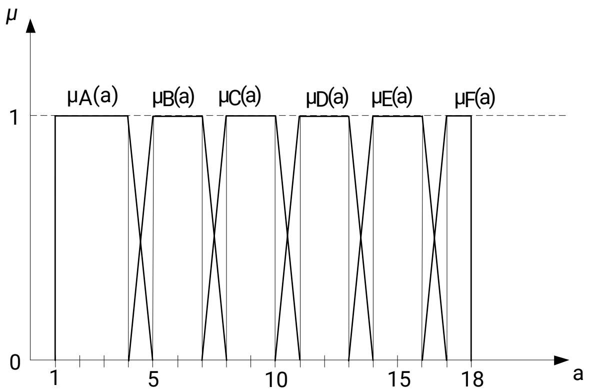

Figure 3. Graphs of functions belonging to fuzzy sets
Note: $\tilde{A}$ (few), $\tilde{B}$ (less than half), $\tilde{C}$ (half), $\tilde{D}$ (more than half), $\tilde{E}$ (many) and $\tilde{F}$ (full)
Source: developed by the author based on fuzzy sets and their universes proposed as an example

Figure 3 shows that the use of subdivision is appropriate to increase the coverage area of the accumulated graph of fuzzy set membership functions and, thereby, reduce the calculation error. But this process cannot be endless for two reasons. Firstly, at a certain level of subdivision, there is actually a transition from fuzzy sets back to clear values, which does not correspond to the task at hand. Secondly, the greater the fragmentation, the more difficult it will be for the side observer to give an estimate of the observation and, as a result, at a certain level, the observer will begin to hesitate between several sets, which will lead to the need to use both in calculations, and thus, in fact, bring the input values back to a lower level of subdivision.

In addition to the question of determining optimal universes, there is a question of possible uncertainty of another quantity – q_{avg}. The average passenger capacity of a fleet of vehicles may be unknown or not clearly defined. For example, the composition of a fleet can be determined by the model range, but not by the number of vehicles of a certain type. In this case, the equation for determining the passenger capacity utilisation rate (1) becomes inversely proportional to another fuzzy variable q_{avg}. Depending on the available variations, the number of fuzzy sets representing the variable, and their universes, the complexity and variability of the model increases. For clarity, a graph of the functions of belonging to a fuzzy variable is given P_k (O_k) considering the variability of the variable q_{avg} (for the universe $\cup_Q = \{18, 24\}$) (Fig. 4).

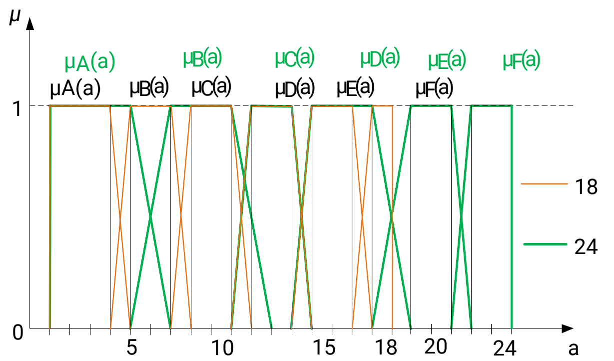

Figure 4. Graphs of functions belonging to fuzzy sets
Note: $\tilde{A}$ (few), $\tilde{B}$ (less than half), $\tilde{C}$ (half), $\tilde{D}$ (more than half), $\tilde{E}$ (many) and $\tilde{F}$ (full) considering the dependence on the fuzzy set $\tilde{Q}$
Source: developed by the author based on fuzzy sets and their universes proposed as an example

Figure 4 shows that the complexity of the model increases significantly as it expands with another fuzzy variable. Considering the fact that the dependence of the passenger capacity utilisation factor on the average passenger capacity of buses is inversely proportional, the dimension of the resulting tensor increases in proportion to the dimension of the fuzzy set universe . Thus, equation (3) takes the final form:

$$n = (2k + 1) \cdot |\cup_Q|, \quad (7)$$

this clearly indicates the need to automate such calculations, due to their ultra-high complexity associated with large amounts of data, and/or a change in the approach of working with a fuzzy variable q_{avg}.

The results obtained demonstrate both the prospects of using fuzzy sets for modelling the passenger capacity utilisation rate, and certain problems associated with the complexity of calculations and the dependence of results on the choice of parameters of membership functions. This highlights the importance of automating calculations and further improving fuzzy data processing algorithms, in particular, to reduce the dimension of the resulting tensor and optimise the model. The proposed approach demonstrates the effectiveness of using fuzzy logic methods for working with data with limited accuracy. The results can be used to further optimise mathematical models in the field of public transport, ensuring adaptation to real conditions of urban transport. This approach helps to improve the accuracy of modelling and efficiency of transport network management in conditions of fuzziness and uncertainty.

The expediency and practical significance of using fuzzy logic methods in modelling transport processes under variable and uncertain conditions, and limitations that should be considered to improve the accuracy and adaptability of models in real conditions, are reflected in many papers that confirm the results of the current study. For example, in a study on the use of a linguistic variable in the monitoring process (Kovtunov *et al.*, 2020), the dependence given in equation (6) was also derived using fuzzy logic. However, this relationship was used to determine the number of terms of a linguistic variable describing the process of monitoring transport communications.

In the dissertation work, I. Kara (2017) considered the use of fuzzy logic to represent vehicle fullness, where fuzzy sets were proposed and graphs of the corresponding membership functions were plotted. Comparison of the graph presented in the dissertation with Figure 1 provided in this study reveals the following. Similar shortcomings were identified, namely, insufficient accuracy of the proposed membership functions, due to the limitation of some values of the universes of the proposed fuzzy sets at the probability mark of 0.4. In contrast to the current study, no further work was carried out to improve accuracy in the paper.

In study by Q. Bao *et al.* (2024) used fuzzy logic as a key tool for solving the two-goal optimisation problem, which aims to consider the uncertainty and multi-factor planning of infrastructure for charging electric vehicles. The study shows the feasibility of using fuzzy logic when working with inaccurate, partially defined or subjective data. N. Jan *et al.* (2023) considered the use of interval-significant complex fuzzy sets for solving decision-making problems in transport strategy. The researchers proposed a model that allows evaluating complex, inaccurate, or contradictory information that occurs during the development of transport strategies in regional planning. The main focus is on multi-criteria tasks where there is a need to consider uncertainty in the input data.

In theoretical research by A. Calvi & S. Pozzi (2021) emphasised that fuzzy logic is a promising mathematical approach for modelling processes in transport engineering that are characterised by subjectivity, ambiguity, uncertainty, and inaccuracy. The main provisions of fuzzy logic systems were presented together with a detailed analysis of their application to solve various problems in transport engineering. Special attention was paid to the importance of fuzzy logic systems as universal approximators in solving transport problems, and the possibilities of further application of fuzzy logic in this area were considered.

S. Niroomand *et al.* (2024) proposed a new approach to solving transport problems with completely intuitive fuzzy parameters. An approach is proposed to transform an intuitive fuzzy transport problem into a multi-criteria one with clear parameters and apply a hybrid optimisation method to solve it. The results of computer experiments demonstrated the effectiveness of the proposed approach in comparison with the existing methods. The above methodology with high efficiency can be useful for solving real transport problems in conditions of uncertainty. In general, the approach to solving the fuzziness problem in the paper is close to the approach proposed in the current study. With the difference that guided by the problem of solving an intuitive-fuzzy problem, the researchers were forced to apply ranking functions in the development of defasification, which actually requires an individual approach to solving each individual problem and, accordingly, the need for careful selection of the appropriate function for a specific problem. Moreover, the approach proposed in this study, although it requires a similar individual approach, is reduced to the formation of universes and, accordingly, the level of subdivision, which is technically a simpler operation in comparison with the selection or formation of a ranking function.

A very close approach to solving the multi-criteria multi-product transport problem was proposed by M. Kar *et al.* (2018). The researchers proposed the use of trapezoidal fuzzy numbers, followed by the use of confidence theory to transform a problem with fuzzy parameters into a deterministic form. The study proposed the application of two approaches to optimisation: the fuzzy programming method and the global criteria method. By testing the example of a transport system for two types of products delivered to three destinations using two types of vehicles, the researchers demonstrated the effectiveness of a combined approach to reduce transportation costs and time. However, the model proposed in the paper was based on the use of trapezoidal fuzzy numbers to model parameters, while the model presented in this paper uses, but is not limited to, trapezoidal fuzzy sets as an example.

Comparison of the obtained results with the data of other studies devoted to the application of fuzzy logic methods in the absence of objective input data in the field of transport, showed that the proposed approach demonstrates compliance with global approaches to solving problems with fuzzy data. In comparison with some of the analysed methods that require the involvement of highly qualified specialists for the development of functions of belonging to fuzzy variables, the approach described in this paper allows the involvement of specialists with a lower level of qualification, sufficient to form universes and determine the necessary degree of subdivision, which is critical in modern conditions of personnel shortage in Ukraine. The results of the study showed the prospects of the proposed model, which not only ensures the accuracy of calculations, but also creates prerequisites for its scaling and implementation in real transport systems with minimal staff training costs.

Conclusions

The conducted research demonstrated the possibility and expediency of using fuzzy logic methods to solve the problem of calculating the passenger capacity utilisation rate in the absence of objective input data. The developed mathematical model allows considering the subjective estimates of an outside observer, presented in the form of fuzzy sets, which significantly increases flexibility and reduces dependence on objective information, which can be difficult to obtain in modern conditions. The proposed model has shown efficiency when working with undefined or subjective data, providing a reduction in calculation error by accumulating membership functions and applying subdivision of fuzzy sets.

During theoretical studies to improve the accuracy of calculations, it was revealed that one of the main problems of applying fuzzy logic is to increase the complexity of calculations due to an increase in the dimension of tensors that occur in multi-stage calculations. This leads to the need to automate modelling and calculation processes. In addition, it was found that the use of a subdivision of fuzzy sets reduces the error of calculations, although at a certain stage this leads to a complication of estimates for outside observers and the impossibility of using a mathematical model for calculations in general.

The results of the study showed that the use of fuzzy logic is a promising area for solving the problems of organising passenger transportation by urban transport in conditions of dynamic changes in passenger flows, or the lack of objective input data. The developed model can be used to evaluate the operation of transport systems in conditions of military operations, migration processes, or other situations that make it difficult to collect accurate data.

Further research should be aimed at optimising the processes of subdivision of fuzzy sets, developing methods for automating calculations, and expanding the model to consider additional factors, such as fleet variability and route changes. It is also advisable to consider using other methods of fuzzy logic, such as linguistic variables or fuzzy sets of Type-2. This will improve the adaptability of transport systems to changing conditions and improve the accuracy of forecasting.

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Conflict of Interest
None.

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Застосування нечітких множин при розрахунку коефіцієнту використання пасажиромісткості в умовах неможливості збору об'єктивних даних

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Анотація. Задачі планування організації перевезення пасажирів міським транспортом у сучасних українських умовах стикаються з новими викликами, зокрема зі складністю або навіть неможливістю отримання точних вхідних даних для проведення розрахунків. Дослідження зосереджено на вирішенні проблеми недоступності точних і актуальних даних для розрахунків організації перевезення пасажирів міським транспортом шляхом використання методів нечіткої логіки. Передбачається, що за умов обмеженого часу для проведення натурних досліджень або впливу військових дій, що спричиняють динамічні зміни пасажиропотоків через міграційні процеси та унеможливлюють отримання даних традиційними методами, запропонований підхід дозволить виконати розрахунки з мінімальною похибкою. На прикладі коефіцієнту використання пасажиромісткості на перегоні транспортного маршруту, що прямо залежить від показника наповненості пасажирами, розглянуто можливість розширення математичної моделі організації перевезення пасажирів на міському транспорті за допомогою підходів нечіткої логіки. Зокрема, йдеться про заміну вхідних величин суб'єктивною оцінкою стороннього спостерігача у вигляді використання нечітких множин. Теоретичне дослідження показало можливість та доцільність використання нечітких множин для вирішення проблеми відсутності об'єктивних вхідних даних при розрахунках коефіцієнту використання пасажиромісткості. Визначено загальні принципи формування універсумів нечітких множин при їх використанні в математичних моделях організації перевезення пасажирів на міському транспорті з метою нівелювання суб'єктивності вхідних даних. Описано вимоги до ступеня перекриття акумульованими функціями належності нечітких множин допустимого рівня субдивізії, що може бути використано з метою зменшення похибки розрахунків та, відповідно, розмірності універсумів нечітких множин. Визначено залежність величини розрядності тензору вихідних результатів від кількісного показника перегонів на маршруті громадського транспорту, що може братися за основу при аналізі складності розрахунків. Показано загальні принципи роботи з нечіткими множинами в даній математичній моделі на прикладі розрахунку коефіцієнту використання пасажиромісткості. Дослідження може бути корисним міським адміністраціям, транспортним компаніям, розробникам програмного забезпечення, експертам з транспортної логістики та науковцям для оптимізації роботи громадського транспорту в умовах нестачі об'єктивних даних і динамічних змін

Ключові слова: громадський транспорт; організація транспортних маршрутів; пасажиромісткість транспорту; нечітка логіка; тензор