FUZZY LOGIC AS A DECISION-MAKING SUPPORT TOOL IN PLANNING TRANSPORT DEVELOPMENT

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Abstract:

Deliberations on transport development indicate that planning is its most significant aspect. One of the key issues in planning is selecting infrastructure projects for completion that will contribute to achieving the development objectives. The important functions of planning, as well as its complexity, indicate the need to use solutions in the decision-making support field. In Poland, in the area of strategic planning of infrastructure development, methods of supporting decision-making aimed at selecting infrastructure projects, taking into account their degree of compliance with strategic goals, are currently not applied comprehensively. The paper aims to address this gap with MCDA solution basing on review of literature combined with the authors' experience in transport planning. Therefore, authors presented a proposed tool for supporting decision-making in planning transport development on a strategic level. The presented method allows for assessing infrastructure development projects in road and rail transport. Such assessments take into account a number of criteria corresponding to the main development directions, i.e. sustainable development and quality of life. Due to the method of formulating development objectives, it has been decided that it will be advantageous to apply fuzzy logic, which enables using natural language in decision-making support systems. To allow practical application of fuzzy logic, the Fuzzy Logic Toolbox package available in the MATLAB environment has been employed. The developed model contains a structure along with defined linguistic variables reflecting the decision-making criteria; also, it includes membership functions, inference rules as well as assessment results. The paper also defines the algorithm of decision-making support procedure. For verification purposes, the decision support model was applied in several real-life project evaluation cases, including a variety of projects in construction, development, and renovation of rail and road infrastructure. The deliberations described in this paper indicate the usefulness of fuzzy logic for supporting decision-making in planning transport development. It's beneficial that the defined criteria can be applied in the case of projects in early preparation phase, enabling their practical application. Implementation of the solution in the MATLAB Fuzzy Logic Toolbox enables achieving fast results of the assessment of decision-maker preference level.

Keywords: fuzzy logic, transport planning, development policy, decision support, MCDA

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1. Introduction

Deliberations on transport development indicate that planning is its most significant aspect. Planning comprises of defining the framework of activities oriented at achieving specific development objectives. On a country-wide scale, in planning transport development, the implementation of plans takes place i.a. by preparation and completion of infrastructure projects, i.e. transport infrastructure construction, expansion, and rebuilding projects. Therefore, the key issue in planning is selecting infrastructure projects for completion that will contribute to achieving the development objectives. The important functions of planning, as well as its complexity, indicate the need to use solutions in the decision-making support field (Semenov & Jacyna, 2022).

The last two decades of studies and analyses indicate unequivocally that the main paradigm of contemporary development is sustainable development, including quality of life (Izdebski & Jacyna, 2018; Cieśla et al., 2020; Franz, 1990; Vuchic, 2005, 2017). In transport system and its infrastructure, the process of shaping sustainable development and quality of life is related to ensuring the implementation of predicted transport needs and harmonisation of EU infrastructure standards on one hand, and to ensuring the achievement of ecological objectives on the other (Komisja Europejska, 2011; Vuchic, 2017).

One should also remember that transport system, due to its scale, covers numerous interactions with the environment, via which the transport system and the environment impact each other. In the literature, a tendency can be observed to group these impacts as follows:

– social impact,
– environmental impact,
– economic impact.

In Poland, in the area of strategic planning of infrastructure development, methods of supporting decision-making aimed at selecting infrastructure projects, taking into account their degree of compliance with strategic goals, are currently not applied comprehensively (Ministry of Infrastructure, 2019).

Bearing in mind the aforementioned, authors of the paper presented a proposed tool for supporting decision-making in planning transport development on a strategic level (Jacyna & Semenov, 2020; Szczepański et al., 2017). Due to the method of formulating development objectives, it has been decided that it will be advantageous to apply fuzzy logic, which enables using natural language in decision-making support systems. To allow practical application of fuzzy logic, the Fuzzy Logic Toolbox package available in the MATLAB environment has been employed. This package enabled the construction of an expert system for transport development planning, which was then used to assess a group of development projects related to transport infrastructure. To assess the tool, four road projects and four rail projects correlated geographically and including construction, expansion and rebuilding of infrastructure were selected.

2. Literature review

2.1. Planning and objectives of transport development

Transport planning is a complex process, however, certain characteristic general steps can be identified (Jacyna et al., 2021; Kowalski et al., 2021; Papacostas, 2005; Vuchic, 2005):

– identifying objectives and tasks,
– gathering data on planning area and system,
– predicting passenger and cargo flow sizes,
– identifying assessment or decision-making criteria,
– developing alternative or competitive solutions,
– assessing solutions,
– decision-making.

The value of social participation is also frequently mentioned, which can have the form of direct consultations, involvement of non-governmental organisations or social representatives advising or directly involved in decision-making (Ortúzar & Willumsen, 2011; von Staden, 2020).

The issues of sustainable development and quality of life are directly related to transport, and, thus, are also the main paradigms of transport development (Izdebski & Jacyna, 2021, Sobota et al., 2018). The authors of (Jacyna et al., 2021) define sustainable transport as an idea conducive to sustainable development, integration of environmental objectives, landscape planning, social and economic public and private entities. Such an integrating and holistic approach to transport development should include:

– the whole system (network),
– all transport branches,
– not only technical and economic factors, but also social and environmental factors,

– the whole functional area (Vuchic, 2005).
The authors of (Ortúzar & Willumsen, 2011) stipulate that, regardless of the changes taking place in the world with time, transport invariably has the same problems, mainly including:

– congestions and delays,
– pollution,
– accidents,
– financial deficits,
– transport exclusion areas.

Transport development objectives in the strategy are defined as follows (Ministry of Infrastructure, 2019):

– creation of an integrated, mutually interconnected transport network,
– increase of transport availability for labour markets, public services,
– increase of inhabitants' mobility in the areas with poor transport availability,
– reduction of negative impact of transport on the environment,
– rational spatial development,
– improvement of the effectiveness of using public funds,
– reduction of transport cost per unit,
– reduction of congestions,
– reliability and efficiency,
– improvement of safety.

2.2. Methods of supporting decision-making in transport development planning

Decision-making support systems can be divided into two basic groups: based on the analysis of a single decision-making criterion, and taking into account multiple criteria. Both of these analysis types are currently frequently used as complementary (Beria et al., 2012; Henke et al., 2020; Tsamboulas et al., 1999) to fully reflect the decision-making problems and its conditions.

Cost and Benefit Analysis is a method based on quantification and monetisation of all the assessed aspects (Beria et al., 2012; Tsamboulas et al., 1999). CBA is widely used in transport infrastructure projects to assess and compare project completion variants. In this area, it is decidedly more consolidated thanks to, among other things, good availability of methodology guides (European Commission, 2014; JASPERS, 2014) and the obligation to use it, when assessing projects co-funded by the EU (European Commission, 2014), or by international organisations, e.g. World Bank . However, it can be seen that in many transport projects the single-criterion assessment based on monetisation can be inadequate or it can even lead to erroneous conclusions. The significant areas insufficiently reflected by CBA in (Vuchic, 2005) are considered to be the value of human mobility, the increase in social equality thanks to improved transport, the reduction of congestions, the improvement of the quality of life, which are naturally subjective and difficult to quantify and monetise. Additionally, the application of monetisation practically excludes the possibility of reflecting the strategic state priorities in the analysis (Tsamboulas et al., 1999).

In the case of assessments of complex decision-making problems, in which bringing all the decision-making criteria down to money values is impossible or unjustified, the decision-making problem is defined by more than one criterion. In such a case, the objectives can also be dependent on each other, or even contradictory (Beria et al., 2012). Multi-criteria analysis (MCA) can be included in this type of decision-making support systems (Beria et al., 2012). This methodology allows for defining compromise solutions, also called pareto-optimum solutions, efficient or undominated (Vincke, 1992), i.e solutions for which a more advantageous solution in relation to one criterion cannot be defined without deterioration in relation to another criterion. In this sense, in MCA there is no one solution that will be the most advantageous from the perspective of all criteria (Tsamboulas et al., 1999), which corresponds to the nature of the decision-making problems in transport planning.

Various approaches can be applied to solve multi-criteria problems. Multi-criteria decision-making can reflect a situation, in which a decision-maker has the problem of (Cieśla et al., 2020; Ehrgott, 2005; Vincke, 1992):

– choice – from the available options, they want to make the choice that is best corresponding to their preferences,
– ranking (arrangement) – they want to rank the available options according to the order from the most to the least preferable,
– classification – they want to divide the available options into classes.

Table 1 presents the multi-criteria methods indicated in the literature.

Table 1. Review of multi-criteria decision-making support methods

Additive Ratio Assessment – ARAS (Multiple Criteria Analysis of Foundation Instalment Alternatives by Applying Additive Ratio Assessment (ARAS) Method, 2010)	Analityc Hierarchy Process – AHP (T. L. Saaty, 1995)
Analityc Network Process – ANP (R. W. Saaty, 2016)	Analytic Centre UTilité Additive – ACUTA (Bous et al., 2010)
Best-Worst Method – BWM (Rezaei, 2015)	BIPOLAR (Górecka, 2017)
Combined Compromise Solution – CoCoSo (Yazdani et al., 2019)	Combinative Distance-Based Assessment – CODAS (Keshavarz Ghorabaee et al., 2016)
Complex Proportional Assessment – COPRAS (Ghorabaee et al., 2015)	DEMATEL (Tzeng & Huang, 2011)
Elimination and Choice Expressing Reality – ELECTRE (Kalifa et al., 2022; Roy, 1990)	Evaluation Based on Distance from Average Solution – EDAS (Ghorabaee et al., 2015)
Factor Relationship – FARE (Ginevîcius, 2011)	Fuzzy Logic Inference System – FIS (Milutinović et al., 2020; Zadeh, 1965)
Ideal Point Approach, The Attribute-Dynamic Attitude Model – ADAM (Zeleny, 1976)	Interactive and Multi-Criteria Decision Making – TODIM (Araújo, 2015)
Kemeny Median Indicator Ranks Accordance – KEMIRA (Krylovas et al., 2014)	Measuring Attractiveness by a Categorical Based Evaluation TecHnique – MACBETH (Bana e Costa et al., 2003)
MAJA (Jacyna & Wasiak, 2015)	Integrated Value Model for Sustainable Assessment – MIVES (Pujadas et al., 2017)
Multi Attribute Utility Approach – MAUT (Schärlig, 1985)	Multi-criteria Optimization and Compromise Solution – VIKOR (Opricovic & Tzeng, 2004)
MUlticriteria Satisfaction Analysis – MUSA (Grigoroudis & Siskos, 2002)	Organization, storage, and summarizing of relational data – ORESTE (Roubens, 1982)
Preference Ranking Organization Method for Enrichment of Evaluations – PROMETHEE (Nassereddine & Eskandari, 2017)	REGIME (Nijkamp & Blaas, 1994)
Ratio Estimation in Magnitudes or deciBells to Rate Alternatives which are Non-DominaTed – REMBRANDT (Lootsma, 1992)	Simultaneous Evaluation of Criteria and Alternatives – SECA (Keshavarz-Ghorabaee et al., 2018)
Simple Additive Weighting – SAW (Hoy et al., 2019)	Simple Multi-Attribute Ranking Technique – SMART (Barfod, 2018)
Step-Wise Weight Assessment Ratio Analysis – SWARA (Keršuliene et al., 2010)	Technique for Order Preference by Similarity to Ideal Solution – TOPSIS (Hamurcu & Eren, 2020)
Treatment of the Alternatives according to the Importance of Criteria – TACTIC (Vansnick, 1986)	Utility Additive – UTA (Jacquet-Lagreze & Siskos, 1982)
Weighted Aggregated Sum Product Assessment - WASPAS (Zavadskas et al., 2012)	

From the perspective of the application of decision-making support methods, it should be specifically noted that the documents indicating development directions, i.e. all the strategies and programmes, use natural language to formulate objectives. Therefore, the expectations they express are of subjective and fuzzy nature. This leads to the phenomenon of vagueness, i.e. potentially different understanding of a given designation by different recipients. Additionally, the objectives that are determined this way usually have no assigned values anticipated in the future (Ministry of Infrastructure, 2019). Fuzzy logic is a solution widely used if there is vagueness present. It enables using natural language in analyses

and using expert's assessments for the creation of inference rules (Bellman & Zadeh, 1970; Rao, 2009; Roy, 1990; The MathWorks Inc, 2021).

3. Application of fuzzy logic as a decision-making support tool

Fuzzy logic is a generalisation of two-valued logic, in which there are two logical values representing false 0 and true 1. Fuzzy logic, on the other hand, anticipates intermediate values between 0 and 1, which represent the degree to which a given statement is true. It has been based on the theory of fuzzy sets formulated by L. Zadeh (Zadeh, 1965). These sets determine object classes without defining unequivocal set limits. Therefore, similarly to logical values, elements of a given set can belong to it to a defined degree.

This property of fuzzy logic is of key importance in the applications analysed in this paper. The development objectives, as mentioned earlier, are expressed in natural language, which is less precise, however, it is closed to human perception and communication. Thanks to the application of fuzzy logic, it is possible to apply linguistic variables, i.e. variables the values of which are expressed not numerically, but descriptively – with words. Therefore, it is classified as the so-called soft computing, i.e. accepting the lack of precision and partial truth (The MathWorks Inc, 2021). Thus, it can be concluded that fuzzy logic imitates human inference method and enables achieving balance between the precision of depiction and the relevance of a problem.

The key issue in formulating linguistic variables is the appropriate selection of the shape of the membership function for linguistic terms of individual variables. At the strategic stage of planning transport development, project characteristics are usually preliminary. This results from the fact that for many projects at this stage there are no detailed study analyses available. With this in mind, it was decided that from the usually applied membership functions it will be sufficient to apply the function with basic shapes, i.e. triangular and trapezoid. Such functions are often used in transport applications and other (Blagojević et al., 2013; Kedia et al., 2015; Marković et al., 2011; Milutinović et al., 2020; Nobakhti et al., 2021; Vahdani et al., 2011). An exemplary membership function family has been presented in Figure 1.

Based on the defined membership functions, the process of fuzzification of sharp values of decision-making criteria takes place, i.e. they are being assigned to individual linguistic terms. The next step is to perform the inference process, which, in the case of fuzzy logic, is related to formulating inference rules. The general form of the rule is as follows:
IF x_1 is A **AND** x_2 is B **THEN** y is C
where: x_1, x_2, y – linguistic variables expressed in natural language, A, B, C – linguistic terms; AND, THEN – plural operations on membership functions. Afterwards, the process includes aggregation of the results of individual inference rules for the resultant function. The final stage is defuzzification of the result enabling the achievement of a specific, numerical resultant value.

4. Model of Decision-Making Support for Transport Development Planning

The assumptions of the model of multiple-criteria decision-making support in transport infrastructure development planning (MPRIT) can be defined as organised eight forms:

$$MPRIT = \langle SM, P, CP, KR, KZL, T, FP, R \rangle \qquad (1)$$
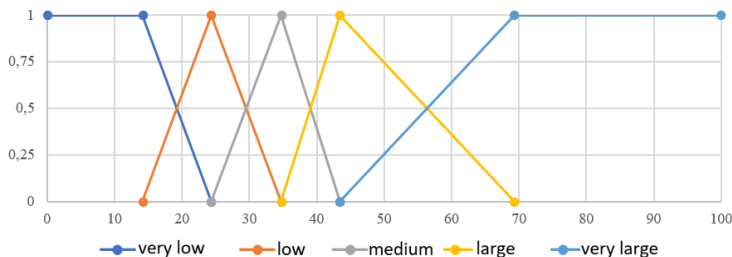

Fig. 1. Membership function family for fuzzy sets "very low," "low," "medium," "large," "very large" where:

structure (SM) of the model understood as the relationships between fuzzy inference modules,
projects (P) which should be assessed,
project characteristics (CP) defining the values of decision-making criteria for individual projects,
decision-making criteria (KR) in the form of linguistic variables (KZL) with linguistic terms (T) and membership functions (FP) for individual linguistic terms,
fuzzy inference rules (R) resulting from answers of the experts.

Bearing in mind the development objectives discussed earlier and the areas of impact on transport infrastructure, three key areas of objective formulation can be indicated (Figure 2) (Rosik & Szuster, 2008):
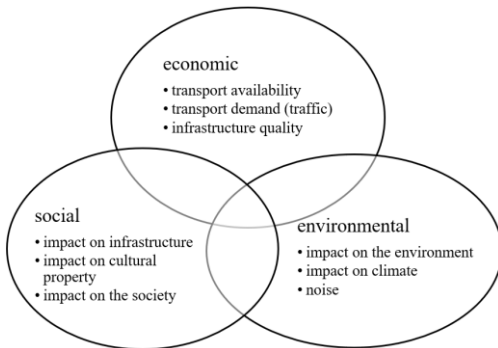– economic,
– environmental,
– social.

Fig. 2. Areas of formulating transport infrastructure development objectives and corresponding decision-making criteria

System of multiple-criteria decision-making support based on fuzzy logic includes the following elements (The MathWorks Inc, 2021):
– fuzzification unit,
– knowledge unit – inference rule base,
– inference unit,
– defuzzification unit.
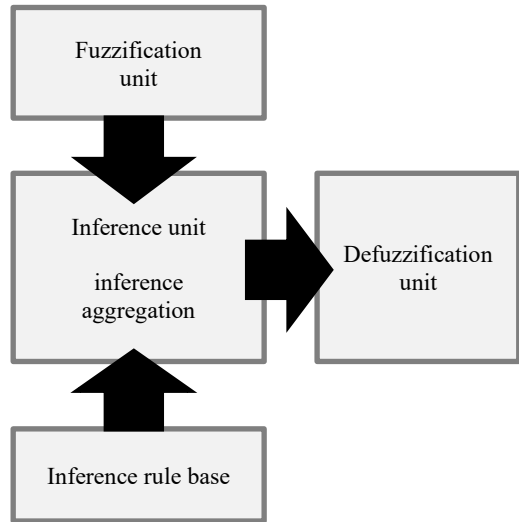The system structure is presented in Figure 3.

Fig. 3. Diagram of fuzzy decision-making support system
Source: own work based on (The MathWorks Inc, 2021).

According to the work of (Devore, 2000), the minimum number of rules required for the proper functioning of inference system equals the product of the number of linguistic terms for all the considered linguistic variables. In the case of a joint application of all nine decision-making criteria in one fuzzy inference module, assuming 5 or 4 linguistic terms, depending on the criterion, the minimum number of rules would exceed one million. Bearing in mind that the creation of rules is a process based on the work of experts, it is justified to limit the number and complexity of rules to maximum three linguistic variables within one inference module.
Therefore, fuzzy inference modules were created separately for each area, with an additional module responsible for synthetic assessment being created afterwards. The modules make up the structure of FIS (Fuzzy Inference System) model with the following interpretations:
FIS$_1$ - fuzzy inference module for the economic-transport area,
FIS$_2$ - fuzzy inference module for the environmental area,
FIS$_3$ - fuzzy inference module for the social area,
FIS$_4$ - fuzzy inference module for the synthetic assessment.

The rules have been determined on the basis of a study conducted among experts. They provided answers in four groups corresponding to the defined fuzzy inference modules. The experts were qualified to the groups according to their education and professional experience. The answers were given by a selection of an inference from the list for the defined rule predecessors. In accordance with the assumptions, 400 inference rules were developed, 125 or 75 for each inference module.

4.1. Decision-making criteria in planning transport development and their parameters

Based on literature review, a set of decision-making criteria was determined for individual areas of defining objectives, as discussed above.

$$KR= \{kr: kr = dt, r, j, ip, k, h, z, zab, s\} \quad (2)$$

where:
dt – transport availability, r – transport demand, j – infrastructure quality, ip – impact on the environment, k – impact on climate, h – noise, z – impact on infrastructure, zab – impact on cultural property, s – impact on the society.

A linguistic variable corresponds to every criterion, allowing to reflect the conditions determined in natural language onto numerical values, so that it is possible to perform the inference process and assessment. Decision-making criteria and their corresponding linguistic variables and membership functions are presented below.
For the purposes of defining the criteria of *impact on the environment, impact on climate, noise, impact on infrastructure, impact on cultural property*, a spatial analysis was performed in the GIS software, using

the data made available by the Head Office of Geodesy and Cartography. Based on this analysis, decision-making criteria parameters and their corresponding linguistic variables were determined.

Transport Availability
In Poland, the Index of Inter-Branch Transport Availability (WMDT) has been assumed as the measure of transport availability, developed by the Committee for Spatial Economy and Regional Planning of the Polish Academy of Sciences. It is based on potential availability and it is described with the formula (Komornicki et al., 2018):
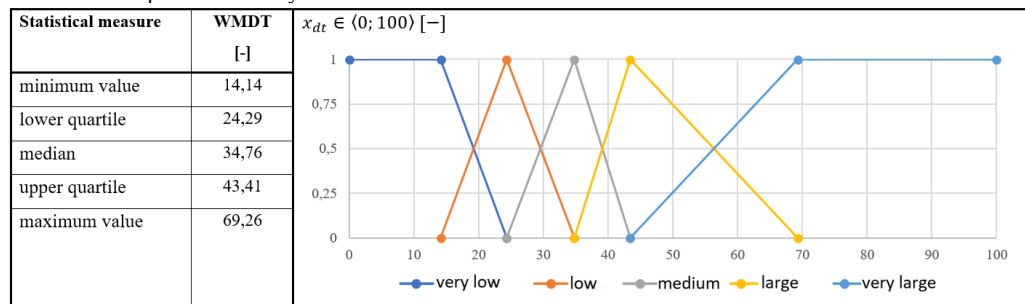
$$A\_i = \sum\_j \llbracket f\_1 (M\_j) f\_2 (c\_{ij}) \rrbracket \quad (1)$$

where:
i, j – number of transport area $i \in \{1,2,3, ..., j\}, i \neq j$, A_i – transport availability of the i transport area, M_j – masses, e.g. number of people or GDP available in the j transport area, c_{ij} – total physical, temporal (time) or economic (cost) distance related to travelling from the i transport area to the j transport area.

WMDT is defined as the sum of transport relationships between given sites, taking into account travel time and the significance of these sites. In passenger transport, the significance is based on population size, and in cargo transport – GDP). The index assumes values from 0 to 100, where, with the increase of transport availability, the index value increases. For the *transport availability* linguistic variable, the family of function membership for linguistic terms has been presented in Table 2.

Table 2. Transport availability

Statistical measure	WMDT [-]	$x_{dt} \in \langle 0; 100 \rangle$ [−]
minimum value	14,14	
lower quartile	24,29	
median	34,76	
upper quartile	43,41	
maximum value	69,26	

Transport Demand

Transport demand shall be understood as a mean daily passenger annual traffic resulting from the forecast for 2050. A network traffic model will be used for the purpose of making the forecast . This is a country-wide four-degree model covering travel generation, travel spatial distribution, selecting means of travel (inter-branch division), traffic distribution in the network. It takes into account individual transport (cars) and mass transit via buses, railway and airplanes (in domestic connections). For the *transport demand* linguistic variable, the family of function membership for linguistic terms has been presented in Table 3.

Infrastructure Quality

An important factor determining investment priorities in transport infrastructure is the quality of the available infrastructure. In the discussed case of road and rail transport, the main qualitative factors can be identified as the ones determining infrastructure efficiency, the costs incurred by a carrier and the technical condition. Based on the reports and analyses of

the carrier market participants, as well as own experiences of the authors, factors representing the quality of road and rail infrastructure were adopted. For the *infrastructure quality* linguistic variable, the family of function membership for linguistic terms has been presented in Table 4.

Impact on the Environment

The characteristic property of road and rail transport infrastructure is its linearity, and, thus, a dividing impact on the environment. This is related to the negative impact on habitats and biodiversity (The Study of Transport Impact on the Environment with Regard to Sustainable Development, 2017). The measure of the criterion, therefore, shall be the area of environmental protection forms intersected by the planned road or railway line referred to the total length of such a road or railway line. For the *impact on the environment* linguistic variable, the family of function membership for linguistic terms has been presented in Table 5.
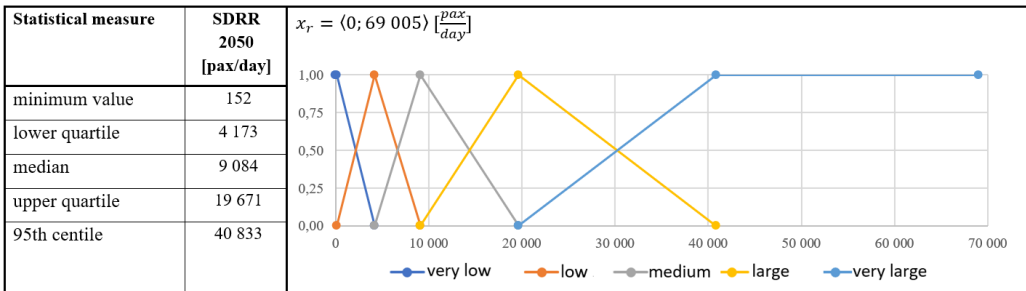
Table 3. Transport demand

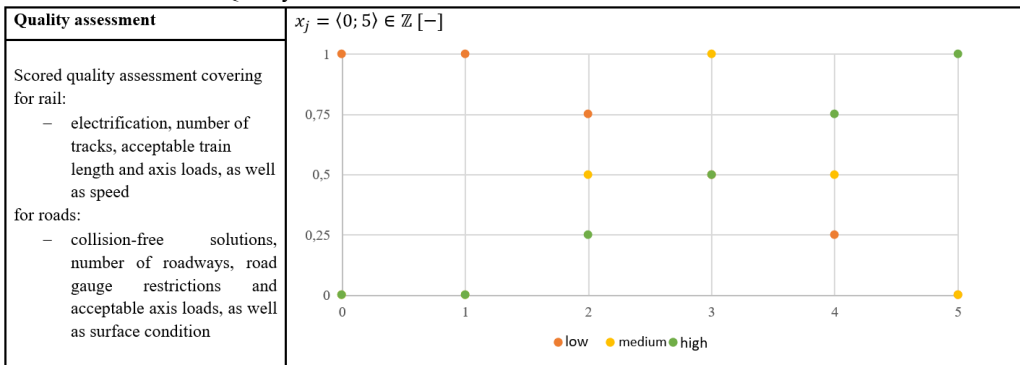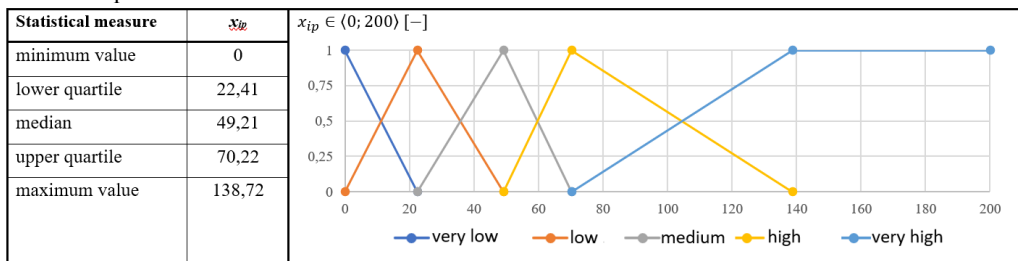| Statistical measure	SDRR 2050 [pax/day]
minimum value	152
lower quartile	4 173
median	9 084
upper quartile	19 671
95th centile	40 833

Table 4. Infrastructure Quality

Quality assessment
Scored quality assessment covering for rail: – electrification, number of tracks, acceptable train length and axis loads, as well as speed   for roads: – collision-free solutions, number of roadways, road gauge restrictions and acceptable axis loads, as well as surface condition

Table 5. Impact on the environment

Statistical measure	x_{ip}	$x_{ip} \in \langle 0; 200 \rangle \, [-]$
minimum value	0	
lower quartile	22,41	
median	49,21	
upper quartile	70,22	
maximum value	138,72	

Impact on the Climate

The main negative impact of human on climate is visible in the emission of greenhouse gases, which is the main source of climate changes. It is estimated that of all the emissions of greenhouse gases in Poland, transport sector is responsible for 13%, and in the case of carbon dioxide alone, it is over 16% (Wiśniewski, 2021). The measure of the criterion, therefore, shall be the value of emission of carbon dioxide equivalent referred to the total length of the road or railway line in question. For the *impact on climate* linguistic variable, the family of function membership for linguistic terms has been presented in Table 6.

Noise

One of the main sources of the negative impact of transport on the environment are acoustic emissions, i.e. noise (Bundesministerium für Verkehr und Digitale Infrastruktur, 2016). Directive 2002/49/EC referring to the assessment and management of noise levels in the environment emphasises the significant role of noise in the impact on the quality of life and the environment. The measure of this criterion, therefore, shall be the number of apartments within the impact area referred to the total length of the road or railway line in question. For the *noise* linguistic variable, the family of function membership for linguistic terms has been presented in Table 7.
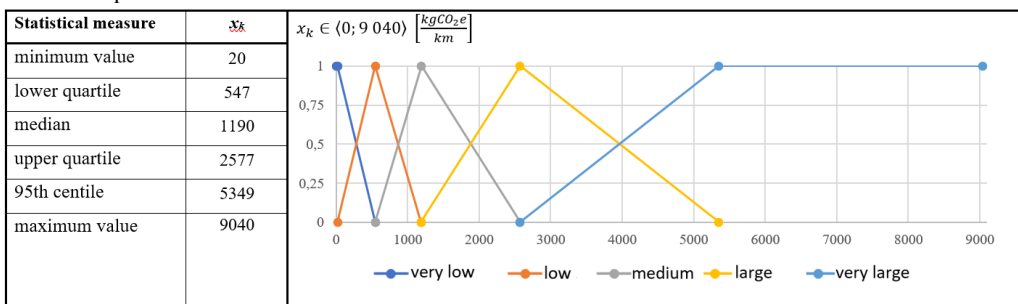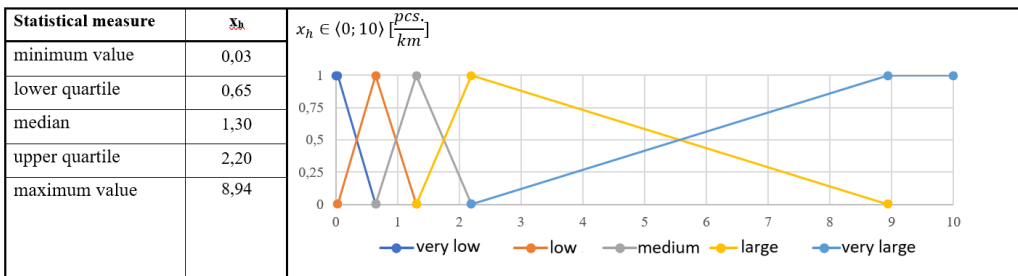
Table 6. Impact on the cilmate

Statistical measure	x_k	$x_k \in \langle 0; 9\,040 \rangle \, \left[\frac{kgCO_2e}{km}\right]$
minimum value	20	
lower quartile	547	
median	1190	
upper quartile	2577	
95th centile	5349	
maximum value	9040	

Table 7. Noise

Statistical measure	x_h	$x_h \in \langle 0; 10 \rangle \, \left[\frac{pcs.}{km}\right]$
minimum value	0,03	
lower quartile	0,65	
median	1,30	
upper quartile	2,20	
maximum value	8,94	

Impact on Infrastructure

Construction of new road and rail infrastructure, but also their expansion and rebuilding, are related to taking over new areas. This activity requires terrain transformation and change of the hitherto planning. This leads not only to increased pressure on the environment, but also, by influencing the infrastructure, it impacts the way of utilising areas by people. The measure of the criterion, therefore, shall be the area of the aforementioned locations referred to the length of the road or railway line. For the *impact on infrastructure* linguistic variable, the family of function membership for linguistic terms has been presented in Table 8.

Impact on Cultural Property

Cultural property includes buildings or mobile objects that, being created by humans, constitute legacy of a past age or event with historical, artistic or scientific value. From the perspective of transport infrastructure development, immobile cultural property and archaeological sites are particularly im-

portant, as their location may interfere with infrastructure. The measure of this criterion, therefore, shall be the number of cultural property objects within the impact area referred to the total length of the road or railway line in question. For the *impact on cultural property* linguistic variable, the family of function membership for linguistic terms has been presented in Table 9.

Impact on Communities

Transport infrastructure investment implementation is related to impact on the society. The problems of social impacts focuses on disrupted historically fixed conditions of social-spatial relationships. Based on the data from the processes of social participation in investment planning and preparation (von Staden, 2020) and professional experiences of the authors related to the processes of public consultations for new transport infrastructure construction projects, areas of infrastructure investment impacts on the society were identified. The measure of the
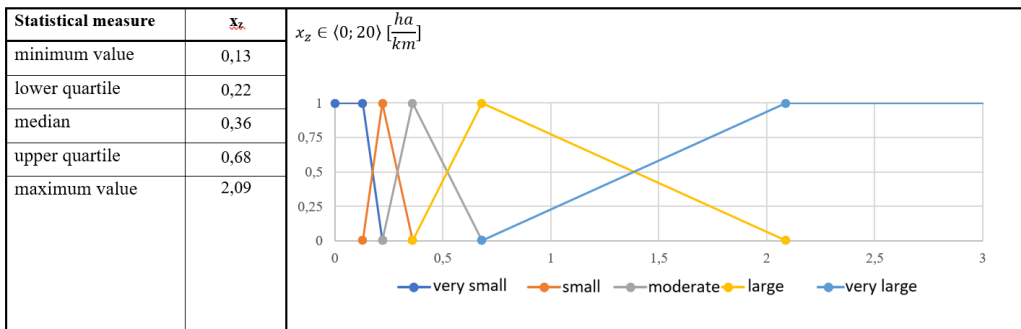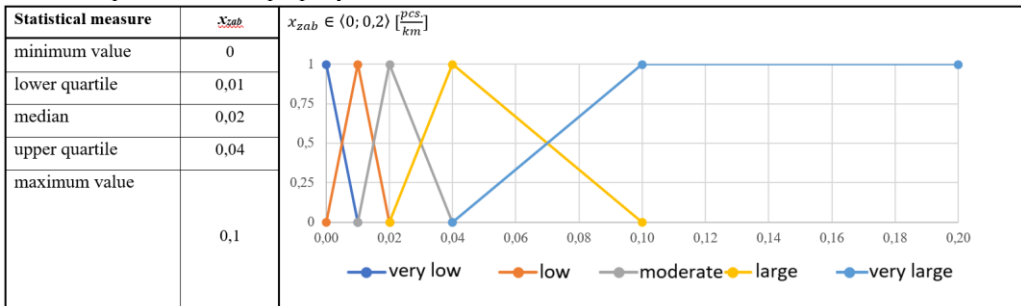
Table 8. Impact on infrastructure

Statistical measure	x_z	$x_z \in \langle 0; 20 \rangle \, [\frac{ha}{km}]$
minimum value	0,13	
lower quartile	0,22	
median	0,36	
upper quartile	0,68	
maximum value	2,09	

Table 9. Impact on cultural property

Statistical measure	x_{zab}	$x_{zab} \in \langle 0; 0,2 \rangle \, [\frac{pcs.}{km}]$
minimum value	0	
lower quartile	0,01	
median	0,02	
upper quartile	0,04	
maximum value	0,1	

criterion, therefore, shall be the intensity of infrastructure impact on the society expressed by the number of identified negative factors. For the *impact on communities* linguistic variable, the family of function membership for linguistic terms has been presented in Table 10.

Additionally, baseline linguistic variables were formulated for individual inference modules, which allows to assign sharp values of baseline variables. The FIS_4 module baseline variable corresponds to the degree of decision-maker's preference for the selection of a given project for completion. Membership functions for baseline variable take into account even distribution of individual linguistic terms on the value of decision-making variable (Figure 4).

4.2. Procedure of decision-making support method in transport development planning and implementation in MATLAB

Algorithm of the decision-making support procedure with the application of fuzzy logic has been divided into four stages:

- stage one (I) – model preparation,
- stage two (II) – project data preparation,
- stage three (III) – project assessment,
- stage four (IV) – project ranking.

The division diagram of the procedure algorithm into stages is presented in Figure 5.

The objective of stage one is specifically to reflect the decision-maker's preferences. Stage I covers the activities related to preparation of the model for work, and, as a rule, it is performed only once. At this stage, strategic objectives related to transport infrastructure development planning are defined.

To enable project assessment, these objective are assigned decision-making criteria. The objectives and criteria expressed in natural language become transformed into numerical values with the application of fuzzy set theory by assigning them linguistic variables and terms, as well as their corresponding membership functions.

The objective of stage two is specifically to reflect the characteristics of the projects in question. For this purpose, project data is prepared, which will then be assessed. The prepared data will correspond to the sharp values of individual linguistic variables. At this stage, it is important that all the projects in question have complete sets of information available. Otherwise, the decision-making support model will not work.

The objective of stage three is to conduct project assessment. Therefore, it covers the basic application of fuzzy logic. Based on the characteristics reflecting the decision-maker's preferences determined in Stage I and the characteristics of the projects determined in Stage II, a fuzzy inference process is performed.

Table 10. Impact on communities

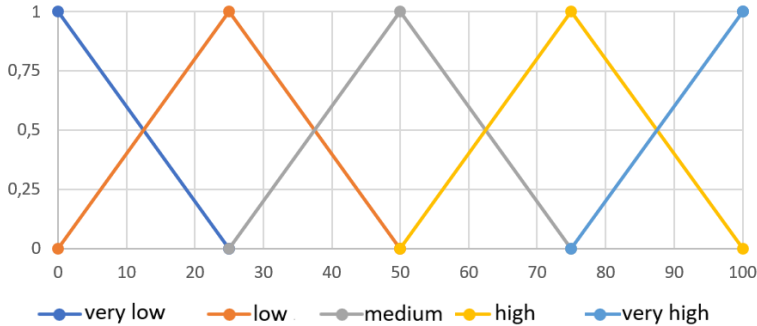| Impact assessment	$x_s = \langle 0; 5 \rangle \in \mathbb{Z} \, [-]$
Scored assessment of impact on the society taking into account interference with the hitherto social relationships (barrier effect), negative impact on the objects important for the community, infrastructure usefulness for local communities (access to infrastructure), planning stability and predictability and planning transparency.	

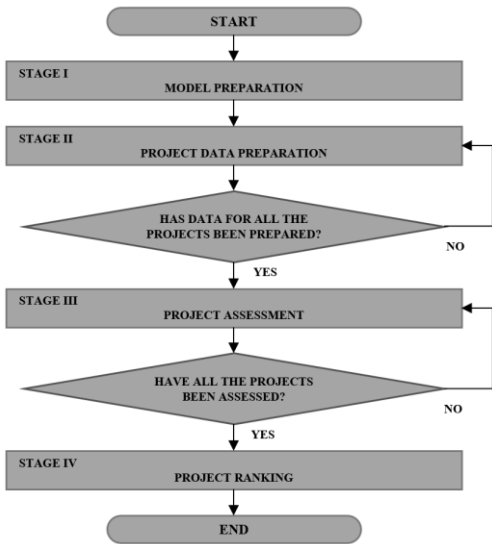Fig. 4. Membership functions for baseline variable

Fig. 5. Division of the algorithm of decision-making
support procedure in planning infrastructure
development

The sharp values of project characteristics undergo the process of fuzzification based on the defined membership functions. Then, a fuzzy inference process will be performed on the basis of the rules developed by experts. The final step will be defuzzification of the resultant value. The sharp value of project synthetic assessment will constitute the determination of the decision-maker's preference degree for directing the given project for implementation.

The objective of stage four is to determine project ranking according to the decision-maker's preferences. The preference degree assessment values obtained in Stage III will enable ranking projects from the most to the least preferred.

5. Case study
5.1. Preparation of a model in the system

For computer implementation of the model, i.e. for the development of expert system, the MATLAB software environment in R2021b version was used with the Fuzzy Logic Toolbox. Fuzzy Logic Toolbox for MATLAB is one of the environments allowing for the creation of an expert system enabling modelling complex behavioural systems with the application of simple logic rules, which can be adopted to fuzzy inferencing.

As part of the computer implementation, the following actions were performed:

- defining inference modules,
- introducing linguistic variables and their membership functions,
- introducing inference rules,
- introducing data for individual projects and recording the results.

The software with a prepared model for one of the inference modules (FIS$_1$) is presented below (Figure 6).

Results of software modelling linguistic variables, their membership functions and inference rules have been presented, for individual inference modules, in the form of area charts (Figure 7).
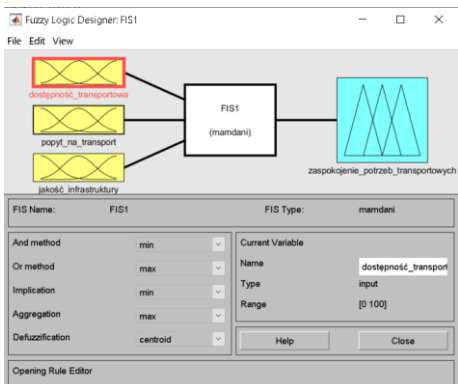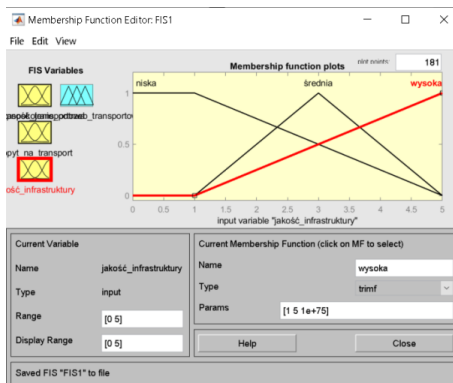
View of the dialogue window for designing the fuzzy logic system FIS$_1$ module
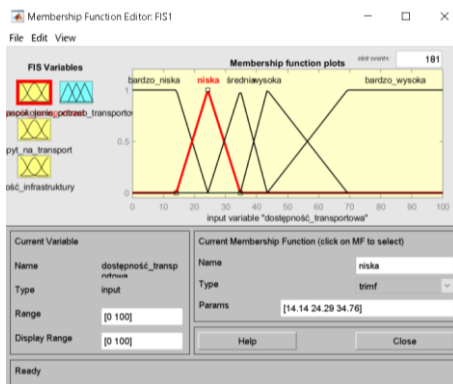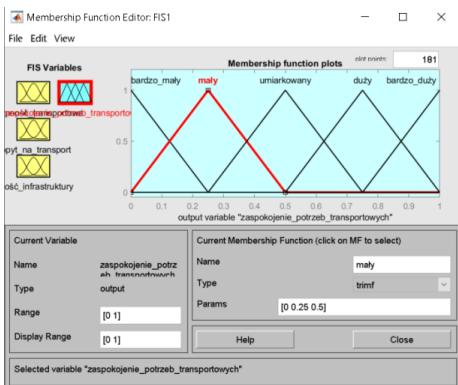

View of the dialogue window of membership functions editor for the linguistic variable of *transport availability*
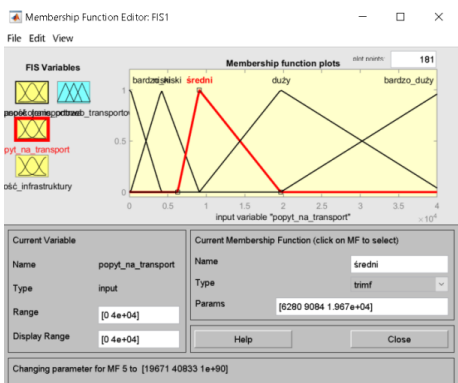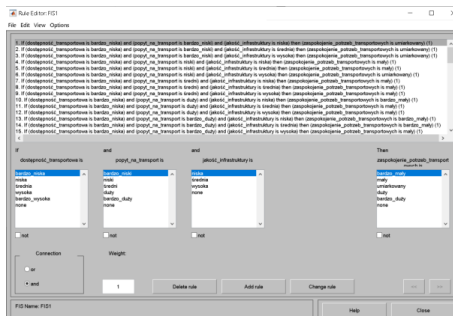

View of the dialogue window of membership functions editor for the linguistic variable of *transport demand*

View of the dialogue window of membership functions editor for the linguistic variable of *infrastructure quality*
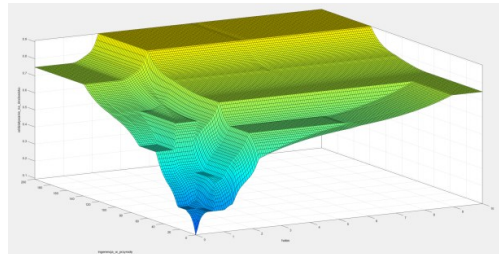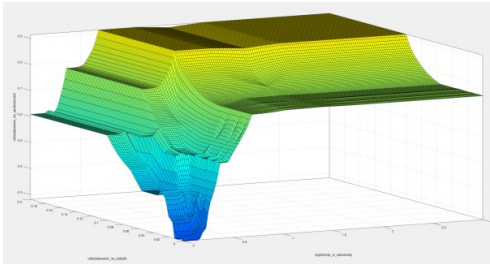

View of the dialogue window of membership functions editor for the linguistic variable of degree of meeting transport needs

View of the dialogue window of rule editor for the FIS1 module

Fig. 6. Model for one of the inference modules (FIS$_1$)
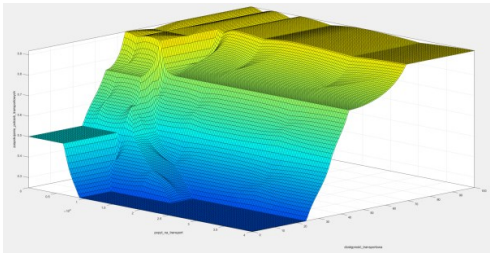
Global modelling results chart for FIS$_1$ module

Global modelling results chart for FIS$_2$ module

Global modelling results chart for FIS$_3$ module
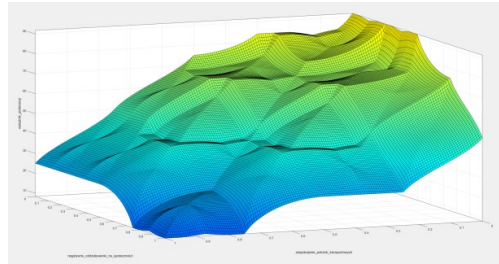
Global modelling results chart for FIS$_4$ module

Fig. 7. Model for one of the inference modules (FIS$_1$)

5.2. Application of fuzzy logic for decision-making support

Four projects of rail infrastructure development and four projects of road infrastructure development were selected for the analysis. Data identifying their characteristics, i.e. the values of linguistic variables, were prepared for all the projects. The results for one of the projects are presented below in more detail. Table 11 presents data for the project named Construction of railway line in the Kraków Swoszowice – Myślenice section.

Table 11. Decision-making criteria values for the project named Construction of railway line in the Kraków Swoszowice – Myślenice section

Criterion name	Unit	Value
Transport availability	[-]	51.33
Transport demand	[passengers/day]	5,000
Infrastructure quality	[-]	0
Impact on the environment	[-]	0
Impact on climate	$(\llbracket kgCO \rrbracket\_2\,e)/km$	135
Noise	$(szt.)/km$	1.53
Impact on infrastructure	ha/km	0.09
Impact on cultural property	[units]	0.09
Impact on the society	[-]	1

This data was entered to the model and model results were obtained for individual inference modules presented in the figure 8.

Results for the other projects were obtained in the same way. The last stage of the method is ranking the projects according to decision-maker's preferences. In accordance with the assumptions, the global index of decision-maker preferences adopts values from 0 to 100, where 100 represents the highest preference.
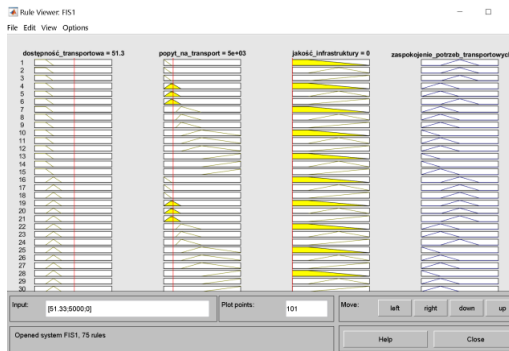
6. Results

Decision-maker's preference assessment, according to the above discussion, has been made in three areas, i.e.:
– economic-transport area,
– environmental area,
– social area.

Then, based on partial preference results from the above areas, the global value of decision-maker's preference index was determined. Project preference assessment results with the application of fuzzy logic and project ranking are presented in Table 12. Value differentiation takes place in the results of project assessment. This refers to the assessment of the global index of preference as well as individual areas. It can be observed that the criteria related to

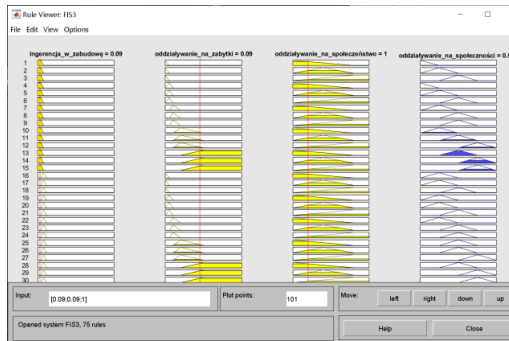the level of negative impact on the environment and society balance the impact of the criterion related to meeting transport needs. The mutual relationships of the impact of individual areas on the final outcome result from the inference rules defined by experts.
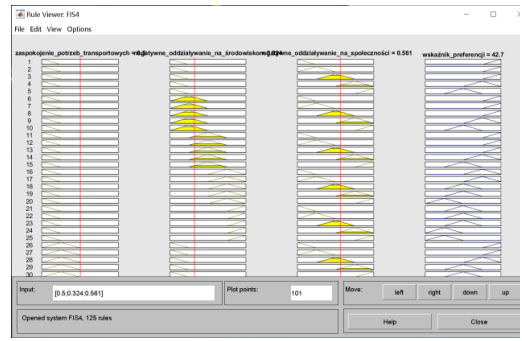

Assessment results for FIS₁ module
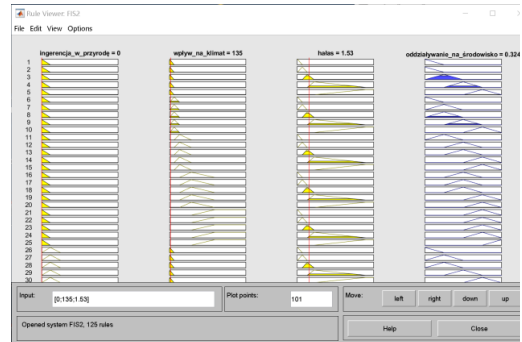
Assessment results for FIS₂ module

Assessment results for FIS₃ module

Assessment results for FIS₄ module

Fig. 8. Results

Table 12 Assessment results of decision-maker preferences

Item	Project name	degree of meeting transport needs	degree of negative impact on the environment	degree of negative impact on local communities	Global index of decision-maker preferences
1.	Construction of S17 express road in the Piaski (S12) – Hrebenne section	0.256	0.520	0.382	61.9
2.	Construction and expansion of railway lines no. 54, 56, 69, and in the Trawniki – Zamość – Hrebenne section	0.500	0.457	0.396	56.1
3.	Construction of S11 express road in the Ostrów Wielkopolski – Poznań (A2) section	0.489	0.584	0.382	50.0
4.	Construction of railway line in the Kraków Swoszowice – Myślenice section	0.500	0.324	0.561	42.7
5.	Construction of railway line 85 in the Kalisz – Poznań Starołęka section	0.611	0.732	0.593	36.2
6.	Construction of railway line 139 in the Tychy – Bielsko-Biała section	0.671	0.624	0.500	34.9
7.	Construction of S1 express road in the Mysłowice – Bielsko-Biała section	0.720	0.907	0.329	29.4
8.	Rebuilding national road no. 7 in the Kraków (A4) – Myślenice section	0.624	0.920	0.806	21.8

7. Summary

The deliberations described in this paper indicate the usefulness of fuzzy logic for supporting decision-making in planning transport development. The presented method allows for assessing infrastructure development projects in road and rail transport. Such assessments take into account a number of criteria corresponding to the main development directions, i.e. sustainable development and quality of life.

It should be considered beneficial that the defined criteria can be applied in the case of projects in early preparation phase, enabling their practical application. The main advantages of applying fuzzy logic as a method of supporting decision-making can include:

– adjusting requirements for input data to the level of information available at the early planning stage,
– the ability to assess road and rail infrastructure projects against a common set of criteria,
– the lack of necessity of organising a large group of experts for the assessment of each project,
– making decision recommendations available in a short time,
– basing decision recommendations on objective and transparent premises.

Implementation of the solution in the MATLAB Fuzzy Logic Toolbox environment enables achieving fast results of the assessment of decision-maker preference level for a given project.

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