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MULTI-CRITERIA HYBRID MODEL OF REGION ASSESSMENT IN THE CONTEXT OF SUSTAINABLE TOURISM

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Abstract. The main goal of the research was to develop a multi-criteria hybrid model for evaluating the region in the context of sustainable tourism, based on the example of the countries of the Visegrad Group. The research uses the mathematical apparatus of expert evaluation, theory of fuzzy sets, fuzzy logic, and multi-criteria evaluation of alternatives. For the first time, an expert method for assessing the level of sustainability of tourism in the region was developed, which was tested on the data of four groups of environmental criteria and sociocultural aspects. For the first time, a multi-criteria model for evaluating the region in the context of sustainable tourism was developed, based on the matrix multiplication method, which derives normalised estimates of regions by groups of sustainable tourism criteria. For the first time, a hybrid model of regional assessment in the context of sustainable tourism has been developed, aggregating the expert level of sustainable tourism development and the normalised estimates of regions by groups of sustainable tourism criteria. As a result, a ranking of regions in the context of sustainable tourism is being built for further decision-making by stakeholders of the new data-driven era. The multi-criteria hybrid model was verified and tested on real data from 2343 respondents of participants of the tourist movement in the V4 countries. The study outcomes will be very useful for policymakers, strategies and action plans, for agencies, national and international organisations, and other entities in the tourism system. They will support the development of a national and international comparative platform and strategic planning processes in the tourism sector aimed at the sector sustainability and the country's economy.

Keywords: sustainable tourism, multicriteria model, fuzzy set, analysis of knowledge, expert systems.

JEL Classification: C24, G32.

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1. Introduction

The tourism sector is very fragmented therefore its individual subsectors face the significantly different challenges under the influence of technological development too. The digital technologies also possess a significant impact on this. The digitalisation processes affect not only the country's economies, but also change their social relations. Global digitalisation reduces the digital divide between the different population groups and thus, it affects the structural changes in the economies. For its successful progress, a systematic investigation of the digital

disparities not only within the countries, but also among the countries is elementary.

The complexity of processes in enterprises requires an exponential increase in data flows. Consequently, this creates pressure for the continuous formation of the digital economy. Digitalisation is accompanied by the constant data flows just right, supporting the development of innovative technologies with dominant artificial intelligence, automation of the processes, and various innovative digital platforms (Kristóf & Virág, 2022; Okhrimenko et al., 2019). The dimension of the functioning of the business environment is altering and the difficulty of the decision-making processes have been increased (Petkovski et al., 2022). It is also related to the fact that digitalisation requires new forms of collaboration and partnerships at all the levels of society. Its success is measured by increasing efficiency and economic growth. Other key factors include the successful transformation of economic sectors, productivity of digital technology use, business attractiveness, and stability of the business environment (Oláh et al., 2022). The sustainability of these parameters is possible through international, national and regional collaboration that will also support the further integration of technological innovations for the global systems and infrastructures.

The role of the state in this process is also significant, demonstrated in the development of digital infrastructures, involving the population in the digital technologies use through a development of the digital competences, supporting digital entrepreneurship, and so on.

Digitalisation strengthens the countries' competitiveness, while the regulatory processes aimed at ensuring the information security of the countries also come to the forefront. It also significantly affects sectoral competitiveness in these countries. From a long-term perspective, digital transformation in tourism can activate many innovation processes that will significantly support the European destination systems' competitiveness (Dredge et al., 2018).

In various fields of tourism, there are the pressures to create new tools enabling effective management and planning of tourism in destinations, including transport infrastructure, environmental, socio-cultural, and other dimensions of the ecosystem (Kourtit et al., 2017; Herrero et al., 2022). Their development requires access to high-quality information data flows, creating a prerequisite for the effective decision-making and planning processes. Managers and decision-makers need strong tools to determine optimal sustainable tourism development scenarios. These tools should help them manage tourism sustainably while considering uncertainties and multiple risks in the evaluation process. This will make it possible to reveal the sector's further innovation potential, to use its new opportunities that digitalisation in sustainable tourism brings and at the same time, to evaluate the economic and social consequences of these technological changes.

The research focuses on assessing regional sustainability in tourism to support data-driven decision-making. It helps tourists choose destinations and authorities improve sustainable tourism. The study incorporates data and knowledge from tourists' experiences and decision-makers' (DM) insights on sustainable tourism development in the region.

The main goal of the conducted research is to develop a multi-criteria hybrid model for evaluating the region in the context of sustainable tourism, using the example of the countries of the Visegrad Group (Czech Republic, Hungary, Poland, Slovakia). The Visegrad Group countries were selected because of their common historical background and different approaches to sustainable tourism, which allows us to evaluate the effectiveness of different strategies. They cover both urban and natural tourist areas and also cooperate in the development of common tourism policies. This makes them a representative case for analysis.

The conducted research has the following structure. The first section showing the appropriate introduction to the topic along with the theoretical background in the second section

are followed by the third section that describes the formal formulation of the problem and the multi-criteria hybrid model for the evaluation of the region in the context of sustainable tourism. The fourth section gives an example of evaluation on real data and thus, it verifies the multi-criteria hybrid model. A discussion of the research outcomes is found in the fifth section. The scientific results obtained for the first time and ideas for future research are described in the sixth section.

2. Overview of domestic and foreign research studies

In the recent period, the digitalisation processes in tourism have been related to its sustainability that is examined from both macroeconomic (Maftuhah & Wirjodirdjo, 2018) and microeconomic (Popkova et al., 2022) perspectives. This allows us to explore the relationships between these dimensions and hence, to identify and to evaluate the relationships between the digitalisation development levels, tourism sector development, sustainability, and economic growth (Filipiak et al., 2023).

The scientific studies consider the digitalisation processes to be an integral part of the global economy (Okhrimenko et al., 2019), whose visible effects are in more rational management of the resources (Bresciani et al., 2021), in the optimisation of the business management processes (Scuotto et al., 2017) along with its structural changes (Matthess & Kunkel, 2020). Digitalisation processes improve the supply chain processes (Calderon-Monge & Ribeiro-Soriano, 2024), accelerate the innovation cycles (Saura et al., 2021), support the internationalisation of the sectors, as well as the creation of the production ecosystems (Suuronen et al., 2022).

Digitalisation helps many communities and stakeholders in the tourism ecosystem. The rapid expansion of tourism destinations has been demonstrated to have important environmental, climate and, socio-political impacts on the countries (Streimikiene, 2023).

Digitalisation also plays an important role in the revival of the sector after the pandemic crisis.

An extensive review of the research studies performed by, for instance, Jiang and Phoong (2023), shows that digitalisation supports the social and economic sustainability of tourism through social development, building cultural awareness, and increasing the technology use. According to Mayer et al. (2023), digitalisation in tourism also supports social justice and environmental integrity that are the foundations of sustainable development. The use of digitalisation by tourists and the use of social media will support the maintenance of relations among tourists and hence, it will lead to digital participation of other stakeholders. Digital tourism has also been very quickly adopted by tour guides, who use various social media platforms for their promotion (Kurnaz et al., 2022).

Digitalisation also helps to build a brand in tourism destinations, implement innovations such as interactive experiences, ecological tours, and ethically engaging tourists in digital innovations (Mbarek & Kummitha, 2024; Schönherr et al., 2023). Ilyas et al. (2023) also presented a plan for responsible tourism based on digitalisation that emphasises balanced personalisation, digital literacy, collaboration of all stakeholders, cultural preservation, and fair access to the benefits of digital tourism.

Bekele and Raj (2025) note that digitalisation in tourism lacks detailed study, limiting understanding of digital innovations and related risks. Sun (2024) highlights that ICT adoption strongly influences the global tourism index, making it a key factor in competitiveness and economic disparities.

2.1. Environmental, economic and socio-cultural dimensions of sustainable tourism

When examining the tourism sustainability issue in the research studies, economic, environmental, and sociocultural factors dominate (Venugopalan & Kumar, 2017; Sofronov, 2017), while resource management, destination management, heritage management, waste management, and the others are also important sustainability factors. The unstable political environment in many countries can possess a different impact on the sustainable tourism processes. Therefore, a complementary investigation of the political influences is also important (Farmaki et al., 2015). This also has an impact on the gradual formation of the sustainable tourism dimensions: biological, economic, socio-cultural, and dimensions of political sustainability (Kantar & Svržnjak, 2017).

Torres-Delgado and Palomeque (2018) developed a consensus system of the indicators to quantify the tourism sustainability at the local level. They classified the investigated indicators into the groups of social, economic, and environmental sustainability. According to Achmad and Yulianah (2022), to ensure economic growth through tourism, it is needed to support the public policies in the economic, social, and environmental fields by the government. Similarly, Schianetz et al. (2007) search for optimal tools for a comprehensive assessment of sustainable tourism that cover the socio-cultural, economic, and environmental aspects. In addition to these fields, Khuntia and Mishra (2014) recommend integrating the indicators of poverty, unemployment, inequality, and independence into the system of sustainable tourism. Baloch et al. (2023) expands the social, economic, and environmental dimensions by health that they consider to be the elementary dimensions of sustainable tourism. The results of their study confirm that health and environmental sustainability are undersized compared to the social and economic aspects.

The policies play an important role in the development and stability of sustainable tourism too (Brendehaug et al., 2016). According to many studies, sustainability needs to be integrated into the tourism planning processes. The sustainable tourism integration should be stimulated by national horizontal integration, bottom-up integration supported by the institutional changes, direct public participation, and active use of planning systems within the particular regions. This creates comprehensive ideas about the complexity of the sustainable tourism system and its dynamics. A significant role is also played by the participating sides (Liburd et al., 2023) and optimal ecosystem management to ensure economic, social, ecological, and cultural sustainability (Irawan & Hartoyo, 2022).

The national certification programmes can also play an important role. Some studies point to the importance of marketing in the sustainability processes, as marketing processes will enable a better understanding of the socio-cultural aspects of destinations and thus, take into account the specific geographic characteristics at the different levels (Sheresheva et al., 2020).

2.2. Fuzzy models in sustainable tourism

The fuzzy models are also applied in a wide variety of the strategic management processes of sustainable tourism (Lee & Hsieh, 2016). The available studies focused on the fuzzy models point to the increasing complexity of the decision-making problems and the data-intensive nature of these methods.

Ziyadin et al. (2019) developed a mathematical model supporting decision-making in the evaluation of the sustainable development of the tourist areas. The model was developed in the Fuzzy Logic Toolbox environment of MATLAB, combining the outcomes of the

economic effects with the environmental and social indicators and enabling the selection of the strategic reference points for sustainable tourism. Skare et al. (2023) developed a fuzzy multi-criteria model for destination image evaluation according to the dependence between costs, number of days of stay, and tourist satisfaction, while this model took into account the levels of sustainable development of the country regions. Vujičić et al. (2020) developed a new model based on fuzzy logic in order to analyse the inner motivations of consumers of the various age levels in the different destinations. Based on a new fuzzy model, they proved how tourist motivations are influenced by age. Tseng et al. (2018) used fuzzy sets and structural modelling to identify key sustainability factors in tourism-social, economic, environmental, and collaborative. Andria et al. (2019) highlight challenges in assessing sustainability due to vague definitions and reliance on qualitative data.

Although the models proposed by Ziyadin et al. (2019), Skare et al. (2024), and Vujičić et al. (2020) demonstrate the effectiveness of fuzzy logic for assessing sustainable tourism, they are usually limited to general characteristics or focus only on specific aspects – economic, social, or environmental. In particular, the model of Mei (2024) focuses only on the environmental status of rural tourism, and the study of Zheng et al. (2022) does not resolve the contradiction between cultural and environmental priorities. Similar limitations are observed in Ocampo (2022), where there is no flexible mechanism for integrating subjective assessments. In contrast, the model proposed in this study is the first to integrate expert assessment with fuzzy logic for multi-criteria balancing of sustainable development. It allows not only to reconcile of conflicting goals (environmental, socio-cultural, economic) but also to adapt the weights of criteria to contextual conditions – which was previously limited in existing approaches (Hosseini et al., 2021; Lou, 2024; Puška et al., 2022).

Despite numerous studies demonstrating the use of fuzzy models for sustainable tourism assessment, the expert method proposed in this study has many differences. For example, Tseng et al. (2018) used fuzzy set theory combined with interpretive structural modeling to identify causal relationships between sustainable tourism factors. Still, this approach has limited consideration of the subjectivity of expert opinion in weighting. Similarly, Hosseini et al. (2021) and Ocampo (2022) applied hybrid fuzzy methods to assess tourism risks and sustainability. Still, they mainly focused on quantitative indicators without detailed consideration of the impact of multi-level subjective judgment. Mei (2024) used AHP for the environmental assessment of rural tourism, but this method does not consider the fuzziness in human perception. Unlike previous approaches, this method uses fuzzy sets to account for expert subjectivity when assigning weights, enabling flexible integration of qualitative and quantitative factors. It uniquely introduces a structured expert decision-making model focused on assessing tourism traffic, not just general sustainability or satisfaction indicators (Mehdiabadi et al., 2021; Skare et al., 2024). Thus, the novelty lies not only in the application of fuzzy logic but also in an improved approach to processing expert information, which allows for a more accurate reflection of the complex nature of assessment in the field of tourism.

Many authors associate the sustainable development of tourism primarily with environmental issues, although the human resources (service providers) and tourists play an important role.

The fuzzy approaches are also successfully applied in the new section of geosciences – in geotourism (Hejazi & Javadi, 2019) as well as in smart e-tourism. Mohammed et al. (2023) proposed a model for the decision-making processes aimed for the intelligent data management applications in e-tourism through a spherical fuzzy rough environment and thus, developed a Spherical Fuzzy Rough Decision by Opinion Score Method (SFR-DOSM) to model the

intelligent e-tourism applications for each category e-tourism. The sustainable development of agritourism through the fuzzy approaches was investigated by Andayani et al. (2022), who developed a prediction model for agro-tourism development applying adaptive neuro-fuzzy inference system method.

Recent studies show growing use of fuzzy models in tourism decision-making, especially for addressing environmental, social, and economic issues in sustainability. AHP and TOPSIS remain the most used MCDM methods, regardless of region (Liao et al., 2023; Abrishamchi et al., 2021).

In addition, research in the last three years shows the active development of fuzzy modeling in sustainable tourism. For example, Zheng et al. (2022) applied fuzzy complex assessment for eco-cultural tourism, and Ocampo (2022) combined FUCOM and the weighted sum method to assess the sustainability of farm locations. Lou (2024) investigated intelligent tourism based on a fuzzy genetic system, and Mohammed et al. (2023) proposed the SFR-DOSM method for decision-making in smart e-tourism. In addition, the ANP-Fuzzy method was effectively applied to take into account climatic factors (Moghtaderi & Mirzaei, 2024), and Ismail et al. (2025) investigated the fuzzy relationships between criteria for the development of community tourism. Skare et al. (2024) developed a multi-criteria fuzzy model for assessing sustainable tourism in the Visegrad Group countries. These achievements demonstrate and confirm the modern scientific basis of the proposed model.

The originality of this study lies in developing an expert method for assessing tourism sustainability, tested on environmental and sociocultural criteria, leading to a hybrid model that aggregates expert evaluations with normalized regional estimates.

The scientific hypothesis is formulated as follows. Suppose the participants of the tourist movement highly evaluate the region in terms of its ecological and socio-cultural components, and there is a high expert assessment of the level of development of sustainable tourism. In that case, it can be stated that the region has a high level of sustainable tourism, which is obtained based on the constructed multi-criteria hybrid model.

3. Materials and methods

3.1. Formal formulation of the evaluation problem

Let us have some set of regions $R=\left\{R_1;R_2;\ldots;R_n\right\}$, which will be evaluated in the context of sustainable tourism. We have that the participants of the tourist movement (experts) $E=\left\{e_1;e_2;\ldots;e_m\right\}$ have visited the region and evaluated its level in the context of sustainable tourism, to various ecological and sociocultural aspects $G_1;G_2;\ldots;G_g$. Each aspect represents a group of sustainable tourism criteria.

Let the multi-criteria hybrid model be presented in the form of an operator:

$$\Psi\left(R,E,G,T,M_{LS},M_{MC},M_{HS}\right)\rightarrow f\left(\xi_{ST}\right), \tag{1}$$

where we have: Ψ – operator deriving ξ_{ST} – quantitative level of the region in the context of sustainable tourism; T – an expert opinion on the level of development of sustainable tourism in the region; M_{LS} – expert method for assessing the level of sustainability of tourism in the region; M_{MC} – a multi-criteria model for evaluating the region in the context of sustainable tourism; M_{HS} – is a hybrid model of regional assessment in the context of sustainable tourism.

The output estimate $f(\xi_{ST})$ contains the content of the validity of decision-making in the context of sustainable tourism at the regional level. The such assessment brings the era of tourism to a new level, driven by data.

The multi-criteria hybrid model for regional assessment in sustainable tourism processes data and knowledge in a data-driven context. It involves three key roles: experts – tourists sharing feedback on their experiences; system analyst – manages the assessment setup; decision maker – uses results to improve regional sustainable tourism.

For a visual interpretation of the multi-criteria hybrid model of regional evaluation in the context of sustainable tourism, a structural diagram is provided, Figure 1.

3.2. Multi-criteria hybrid model of region assessment in the context of sustainable tourism

At the first stage of the model, an expert assessment of the level of sustainability of tourism in the region is carried out using an expert method – M_{LS}.

Let all indicators be divided into groups of sustainable tourism criteria $G_1;G_2;\ldots;G_g$, $h=\overline{1,g}$, namely: $G_1=\left(K_{11};K_{12};\ldots;K_{1g_1}\right),G_2=\left(K_{21};K_{22};\ldots;K_{2g_2}\right),\ldots,G_g=\left(K_{g1};K_{g2};\ldots;K_{gg_g}\right)$. Each criterion is a question formulated in relation to expected and actual experience.

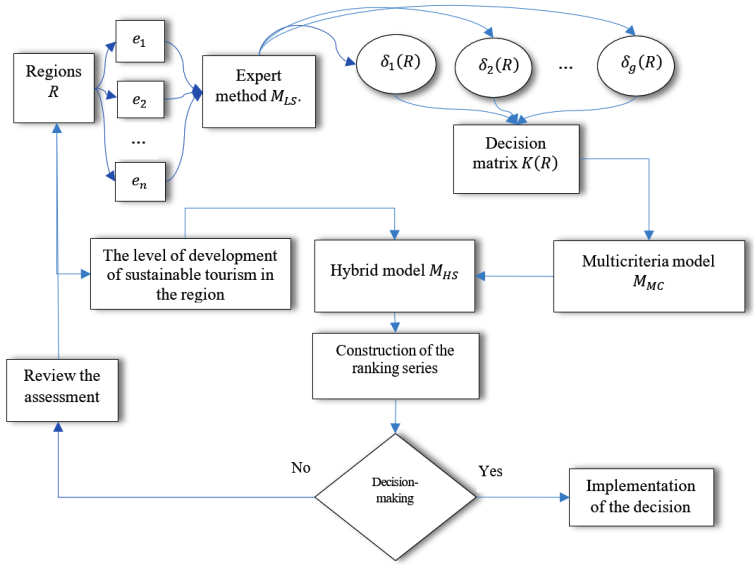

Figure 1. Structural diagram of the multi-criteria hybrid model

The expert evaluates positive and negative aspects of sustainable tourism based on expected and actual experiences, using terms $U=\{U_1;U_2;U_3;U_4\}$ with Boolean-form questions and answers:

1. What POSITIVE aspects did you EXPECT/ASSUMED to experience in terms of sustainable tourism in the region? U_1 = {"Unexpected" = 0; "Expected" = 1}.

2. What POSITIVE aspects did you actually EXPERIENCE in terms of sustainable tourism in the region? U_2 = {"Haven't experienced" = 0; "Experienced" = 1}.

3. What NEGATIVE aspects did you EXPECT to experience of sustainable tourism in the region? $U_3 = \{$"Unexpected" = 0; "Expected" = 1$\}$.

4. What NEGATIVE aspects did you actually EXPERIENCE in terms of sustainable tourism in the region? $U_4 = \{$"Haven't experienced" = 0; "Experienced" = 1$\}$.

Thus, for each expert, a set of his judgments is obtained according to selected groups of criteria, which are translated into Boolean variables $\lambda_k = \{0;1\}$, $k = \overline{1,4}$, where: $\lambda_1(\lambda_2)$ positive aspects to the expected (real) experience, $\lambda_3(\lambda_4)$ negative aspects regarding the expected (real) experience.

The sum of scored points and normalized assessment are calculated separately for groups of criteria:

$$S_{hk} = \sum_{p=1}^{g_h} \left(\lambda_{hk}\right)_{hp}, \; h = \overline{1,g}; \;\; k = \overline{1,4}; \tag{2}$$

$$\mu_h(e) = \frac{1}{2} * \left(\left(\frac{S_{h2}}{g_h} \right)^{\alpha_1} + \left(1 - \left(\frac{S_{h4}}{g_h} \right)^{\alpha_2} \right) \right), \; h = \overline{1,g}, \tag{3}$$

where the values of α_1, α_2 can consider the expected and real experience, taking into account positive and negative aspects based on the theory of fuzzy logic. Then, for positive aspects, the values of α_1 are determined by the following system of logical statements:

IF $(S_{h1} = S_{h2})$ THEN $\alpha_1 = 1$, or IF $(S_{h1} < S_{h2})$ THEN $\alpha_1 < 1$, or IF $(S_{h1} > S_{h2})$ *THEN* $\alpha_1 > 1$.

For negative aspects, the value of α_2 is:

IF $(S_{h3} = S_{h4})$ THEN $\alpha_2 = 1$, or IF $(S_{h3} < S_{h4})$ THEN $\alpha_2 > 1{,}5$, or IF $(S_{h3} > S_{h4})$ *THEN* $1 < \alpha_2 < 1{,}5$.

The construction of such a system of logical statements became possible with the help of model verification on real evaluation data of 2,343 respondents (Data from 2,343 respondents, 2023). Calibration was performed using fuzzy logic on real tourist experiences, with iterative tuning to minimize error between expected and actual satisfaction (Polishchuk, 2019).

As a result, we get: $\mu_h(e_1(R)), \mu_h(e_2(R)), \ldots, \mu_h(e_m(R)), \; h = \overline{1,g}$.

After that, within the limits of one region, one normalized assessment of all experts regarding groups of sustainable tourism criteria is derived, according to the following formula:

$$\delta_h(R) = \frac{1}{m} \sum_{i=1}^{m} \mu_h(e_i(R)), \; h = \overline{1,g}. \tag{4}$$

The received estimates $\delta_h(R) \in [0;1]$ characterize the level of sustainability of tourism in the visited region R in terms of groups of sustainability criteria $G_1, G_2, \ldots, G_g$. After that, this evaluation process is repeated for all visited regions R. The evaluation results are presented in the form of a normalized dimension matrix $g \times n$:

$$K(R) = \begin{pmatrix} \delta_1(R_1) & \delta_1(R_2) & \ldots & \delta_1(R_n) \\ \delta_2(R_1) & \delta_2(R_2) & \ldots & \delta_2(R_n) \\ \ldots & \ldots & \ldots & \ldots \\ \delta_g(R_1) & \delta_g(R_2) & \ldots & \delta_g(R_n) \end{pmatrix}. \tag{5}$$

In the $K(R)$ matrix, the estimates $\delta_h(R_j)$ represent the generalized opinions of experts on the h-th group of stability criteria for the j-th region, $h=\overline{1,g}$, $j=\overline{1,n}$.

At the second stage of the model, there is a multi-criteria assessment of the region in the context of sustainable tourism using the model – M_{MC}.

Next, the alternatives of the decision matrix $K(R)$ are evaluated by using models and methods of problems of multi-criteria selection of alternatives. As a result, aggregated estimates of alternative regions $(\Delta_1,\Delta_2,\ldots,\Delta_n)$ are obtained in the context of sustainable tourism. To do this, you can use a matrix multiplication method is proposed, which was developed by one of the authors of the article (Polishchuk, 2019). Thus, normalized assessments of regions $(\Delta_1,\Delta_2,\ldots,\Delta_n)$, are obtained, according to groups of sustainable tourism criteria.

At the third stage of the model, an expert opinion on the level of development of sustainable tourism in the region is considered, as well as an assessment using a hybrid model – M_{HS}.

Let DM, based on its knowledge and reasoning, establish the level of development of sustainable tourism separately by R_j regions. A term set of linguistic variables is used to establish such a level, for example, $T=\{t_1;t_2;\ldots;t_5\}$. For example, linguistic conclusions regarding the level of development of sustainable tourism in the region are formalized as follows: t_1 – low, t_2 – below average, t_3 – average, t_4 – above average, t_5 – high.

To be able to compare data, it is necessary to aggregate expert opinions on the level of development of sustainable tourism in the region and standardized assessments of regions by groups of sustainable tourism criteria. First, the term-set of linguistic variables T is represented on the numerical interval $[a_1;a_6]\subset[0;1]$ to delimit the terms: $t_1\in[0;a_1]$, $T_1\in[a_1;a_2]$, $t_2\in[a_1;a_2]$, $t_3\in[a_2;a_3]$, $t_4\in[a_3;a_4]$, $t_5\in[a_4;1]$. $T_5\in[a_5;a_6]$ The value of the gap breakdown was adjusted by the authors of the article, who are experts in regional tourism in the V4 countries. It was obtained that $t_1\in[0;0,3]$, $T_1\in[a_1;a_2]$, $t_2\in[0,3;0,5]$, $t_3\in[0,5;0,7]$, $t_4\in[0,7;0,9]$, $t_5\in[0,9;1]$. $T_5\in[a_5;a_6]$

Next, ξ_{ST} quantitative levels of the region in the context of sustainable tourism are calculated:

$$\xi_{ST}(R_j)=\begin{cases}a_1\cdot\Delta_j, & if \quad T=t_1;\\ a_2\cdot\Delta_j, & if \quad T=t_2;\\ a_3\cdot\Delta_j, & if \quad T=t_3;\\ a_4\cdot\Delta_j, & if \quad T=t_4;\\ 1\cdot\Delta_j, & if \quad T=t_5.\end{cases} \quad j=\overline{1,n}. \tag{6}$$

Based on the estimates $(\xi_{ST}(R_1),\xi_{ST}(R_2),\ldots,\xi_{ST}(R_n))$, a ranking of regions is formed, allowing the DM to select the top-ranked option.

4. Results

The study verified and tested the multi-criteria hybrid model of regional assessment in the context of sustainable tourism on real data in the countries of the Visegrad Group (Czech Republic, Hungary, Poland, Slovakia) (Data from 2,343 respondents, 2023). Data were collected from respondents in the period from March to December 2021. As a result, a set of data

was obtained from 2,343 respondents the participants of the tourist movement who visited the regions of the V4 countries for the period from 2017 to 2021. The research questionnaire was structured and contained 132 general questions, which were divided into 16 groups of criteria and were aimed at studying experiences and impressions related to tourism. The very procedure of data collection from the participants of the tourist movement became possible thanks to the cooperation of several organizations. We note that the obtained data meet the requirements of forming a data sample since the respondents met the demographic requirements and covered the full set of elements of the investigated issues. The selection of respondents was carried out on the basis of the criteria of demographic distribution and attraction of participants of the tourist movement visiting the regions of the V4 countries. Measures were foreseen to minimize sampling bias, including balanced regional coverage and exclusion of incomplete or poor-quality responses. To check the internal consistency of the questionnaire, Cronbach's α coefficient was calculated for the main groups of criteria, which allowed us to assess the level of consistency of the respondents' answers. The obtained Cronbach's α values for each group of criteria exceeded the generally accepted threshold of 0.7, which indicates high reliability and internal coherence of the questionnaire (Data from 2,343 respondents, 2023). This means that the questions within each category measure the same aspect of the phenomenon under study, and the results obtained are stable and reproducible. Additionally, an analysis of the factor structure of the questionnaire was conducted, which confirmed the correspondence of the selected criteria to the theoretical model of assessing sustainable tourism. Thus, the reliability check ensured the validity of the conclusions obtained within the framework of the study.

The authors conducted many experiments, based on the entire set of real data, using a multi-criteria hybrid model for evaluating the region in the context of sustainable tourism. To replicate the research by other interested parties, the manuscript illustrates an example of the evaluation of data fragments.

The United Nations World Tourism Organization (UNWTO) promotes Sustainable Development Goal 8 ("decent work and economic growth") by fostering responsible tourism based on data and knowledge. As the custodian for tourism and sustainable tourism, its goals include (The World Tourism Organization, 2023):

- By 2030, implementing policies that advance sustainable tourism, create jobs, and support local culture and food (SDG 8).
- Developing tools to monitor the impact of sustainable tourism on job creation and the promotion of local culture and products (SDG 12).

In response to this, an assessment of the level of the region in the context of sustainable tourism is proposed, which includes indicators with an ecological component of sustainable tourism, related to the protection of the natural environment and resources, and sociocultural tools: G_1 – environment; G_2 – culture, local customs, and traditions; G_3 – food and drinks at the destination; G_4 – the attitude of local residents to visitors at the destination.

Group of criteria G_1 is tourism aspects related to the environment. This group consists of the following criteria: K_{11} – the attractiveness of the environment; K_{12} – peace at the destination; K_{13} – noise level at the destination; K_{14} – level of green infrastructure at the destination; K_{15} – the feeling that the environment and its resources are cared for by the government and local residents.

The second group of criteria G_2 is culture, local customs, and traditions. It consists of the following criteria: K_{21} – comfort in understanding the language of the population and staff; K_{22} – accessibility of art; K_{23} – the presence of cultural satisfaction; K_{24} – a variety of options for spending free time; K_{25} – the friendly culture of residents.

The third group of criteria G_3 is food and drink at the destination. This includes the following criteria: K_{31} – delicious local food; K_{32} – the variety of food; K_{33} – the variety of drinks; K_{34} – wine/cheese tasting opportunities; K_{35} – wine and beer routes; K_{36} – availability of ordering food at different times.

The fourth group of criteria G_4 is the attitude of local residents to visitors to the destination. This group consists of the following criteria: K_{41} – honesty of residents and buyers; K_{42} – honesty of guides or travel agents; K_{43} – warm hospitality of residents; K_{44} – good social skills of the population; K_{45} – good social skills of service personnel.

The expert evaluates expected vs. actual experiences by selecting the most accurate option from $U = \{U_1;U_2;U_3;U_4\}$ for each tourism aspect.

For a visual interpretation of the assessment, for example, data on some expert e_7 for the first group of criteria, after a trip to the Žilina region (Slovakia) in 2019 (Data from 2,343 respondents, 2023), Table 1, is presented.

At the first stage of the model, an expert assessment of the level of sustainability of tourism in the region is carried out using the following expert method – M_{LS}.

Table 1. Input expert data from the respondent e_7

Group of criteria	Criteria	Positive aspects		Negative aspects	
		Expected experience	Real experience	Expected experience	Real experience
G_1	K_{11}	Expected	Experienced	Unexpected	Haven't experienced
	K_{12}	Expected	Experienced	Unexpected	Haven't experienced
	K_{13}	Expected	Experienced	Unexpected	Haven't experienced
	K_{14}	Expected	Haven't experienced	Unexpected	Haven't experienced
	K_{15}	Expected	Haven't experienced	Unexpected	Haven't experienced
G_2	K_{21}	Expected	Experienced	Unexpected	Haven't experienced
	K_{22}	Expected	Experienced	Unexpected	Haven't experienced
	K_{23}	Expected	Experienced	Unexpected	Haven't experienced
	K_{24}	Expected	Experienced	Unexpected	Haven't experienced
	K_{25}	Expected	Experienced	Unexpected	Haven't experienced
G_3	K_{31}	Expected	Experienced	Unexpected	Haven't experienced
	K_{32}	Expected	Experienced	Unexpected	Haven't experienced
	K_{33}	Expected	Experienced	Unexpected	Haven't experienced
	K_{34}	Unexpected	Haven't experienced	Expected	Experienced
	K_{35}	Unexpected	Haven't experienced	Expected	Experienced
	K_{36}	Expected	Experienced	Unexpected	Haven't experienced

End of Table 1

Group of criteria	Criteria	Positive aspects		Negative aspects	
		Expected experience	Real experience	Expected experience	Real experience
G_4	K_{41}	Unexpected	Haven't experienced	Unexpected	Haven't experienced
	K_{42}	Expected	Experienced	Unexpected	Haven't experienced
	K_{43}	Expected	Experienced	Unexpected	Haven't experienced
	K_{44}	Expected	Experienced	Unexpected	Haven't experienced
	K_{45}	Expected	Experienced	Unexpected	Haven't experienced

All expert judgments according to selected groups of criteria are translated into Boolean variables. Next, the sum of the scored points according to Eq. (2) is calculated separately for groups of criteria G_1, G_2, G_3, G_4 The calculated results are given in Table 2.

Table 2. Derivation of the results of the calculation from the respondent e_7

	Positive aspects		Negative aspects	
	Expected experience	Real experience	Expected experience	Real experience
S_1	5	3	0	0
S_2	5	5	0	0
S_3	4	4	2	2
S_4	4	4	0	0

Next, within the criteria group, a quantitative standardized assessment is derived, considering the real experience of the participants of the tourist movement, using formula (3). Moreover, research was conducted on the received real data and established. For positive aspects: If $(S_{h1} = S_{h2})$ Then $\alpha_1 = 1$, or If $(S_{h1} < S_{h2})$ Then $\alpha_1 = \frac{3}{5}$, or If $(S_{h1} > S_{h2})$. Then $\alpha_1 = \frac{6}{5}$. For negative aspects: If $(S_{h3} = S_{h4})$ Then $\alpha_2 = 1$, or If $(S_{h3} < S_{h4})$ Then $\alpha_2 = \frac{8}{5}$, or If $(S_{h3} > S_{h4})$. Then $\alpha_2 = \frac{7}{5}$. We obtain the following results: $\mu_1 = 0.667$; $\mu_2 = 1$; $\mu_3 = 0.333$; $\mu_4 = 0.9$.

After that, within the limits of one region, one normalized assessment is derived for all experts regarding the groups of criteria of sustainable tourism, according to formula (4). The evaluation results for all regions are given in (Data from 2,343 respondents, 2023). Let, without reducing generality, nine regions of V4 countries are selected for further calculations, Table 3.

At the second stage of the model, there is a multi-criteria assessment of the region in the context of sustainable tourism using the model – M_{MC}.

Alternatives $R_1, R_2, \ldots, R_9$ regions are evaluated based on the proposed method of matrix multiplication (Polishchuk, 2019). As a result, estimates are obtained: $\Delta_1 = 0.117$; $\Delta_2 = 0.107$; $\Delta_3 = 0.107$; $\Delta_4 = 0.109$; $\Delta_5 = 0.116$; $\Delta_6 = 0.109$; $\Delta_7 = 0.113$; $\Delta_8 = 0.112$; $\Delta_9 = 0.11$.

Table 3. The output of calculation results using the expert method – M_{LS}

No.	Region	Country	δ_1	δ_2	δ_3	δ_4
R_1	Banská Bystrica Region	SK	0.837	0.849	0.517	0.894
R_2	Budapest is the capital	HU	0.712	0.819	0.531	0.793
R_3	Bratislava Region	SK	0.71	0.828	0.53	0.785
R_4	South Bohemian region	CZ	0.785	0.81	0.537	0.774
R_5	South-Moravian region	CZ	0.822	0.892	0.568	0.82
R_6	Pilsen Region	CZ	0.823	0.753	0.512	0.819
R_7	Prešov Region	SK	0.82	0.813	0.484	0.846
R_8	Podkarpackie Voivodeship	PL	0.793	0.807	0.535	0.836
R_9	Pomeranian Voivodeship	PL	0.756	0.824	0.484	0.823

At the third stage of the model, an expert opinion on the level of development of sustainable tourism in the region is considered and an assessment is carried out using a hybrid model – M_{HS}.

Let DM, based on its knowledge and reasoning, establish the level of development of sustainable tourism separately by region: $T(R_1)=t_4$; $T(R_2)=t_5$; $T(R_3)=t_5$; $T(R_4)=t_4$; $T(R_5)=t_4$; $T(R_6)=t_5$; $T(R_7)=t_3$; $T(R_8)=t_3$; $T(R_9)=t_4$.

Next ξ_{ST} quantitative levels of the region in the context of sustainable tourism are calculated using the formula (6): $\xi_{ST}(R_1)=0.1057$; $\xi_{ST}(R_2)=0.1071$; $\xi_{ST}(R_3)=0.107$; $\xi_{ST}(R_4)=0.098$; $\xi_{ST}(R_5)=0.1048$; $\xi_{ST}(R_6)=0.1094$; $\xi_{ST}(R_7)=0.0788$; $\xi_{ST}(R_8)=0.0782$; $\xi_{ST}(R_9)=0.0986$.

Based on the obtained estimates $\left(\xi_{ST}(R_1),\xi_{ST}(R_2),...,\xi_{ST}(R_9)\right)$ a ranking series of alternative regions in the context of sustainable tourism is constructed: R_6; R_2; R_3; R_1; R_5; R_9; R_4; R_7; $R8$. As you can see, the best region according to the multi-criteria hybrid model for evaluating the region in the context of sustainable tourism is Pilsen Region.

5. Discussion, implications and limitations

The paper developed a multi-criteria hybrid model of region assessment in the context of sustainable tourism, which, based on the impressions of the participants of the tourist movement regarding the tourist aspects of sustainable tourism, as well as based on the expert level of sustainable tourism development in the region, derives a ranking of alternative regions in the context of sustainable tourism. For this purpose, the following were developed: an expert method for assessing the level of sustainability of tourism in the region; a multi-criteria model for evaluating the region in the context of sustainable tourism; a hybrid model of regional assessment in the context of sustainable tourism; the developed multi-criteria hybrid model was verified on real data in the regions of the V4 countries; an example of building a ranking series in the context of sustainable tourism based on the data of nine regions of the V4 countries is illustrated.

5.1. Theoretical implications

The aim of our study was the development of an expert method for evaluating the tourism sustainability level, tested on the data from the four groups of the environmental criteria and the socio-cultural aspects. A hybrid model of the regional evaluation in the context of sustainable tourism was developed that aggregates the expert level of sustainable tourism development and the normalised estimates of the regions according to the groups of the sustainable tourism criteria. This model reflects on the current challenges of sustainable tourism, as well as on the declared need to find the tools for evaluating the interconnectedness of the environmental dimensions, intelligent specialisation and innovation processes in the context of spatial sustainability (Romao & Neuts, 2017).

In the tourism industry, a major challenge is to connect the economic interests of the sector with the creation of social and environmental values based on the sustainability principles, which will create a space for further multidimensional investigations of the factors' effects and for the creation of multivariate models of sustainable tourism. This will directly support the further development of the decision-making tools and methodological platforms.

Tourism dynamics differ across Europe: resource-rich countries often have weak socio-economic outcomes and rely on low-value tourism, while highly tourism-dependent countries face low GDP and high unemployment. This calls for new strategies to ensure regional balance. Many studies seek trade-offs between environmental, economic, and social goals, requiring analysis of conflicting criteria (Streimikiene et al., 2021; Postma et al., 2017). Digital technologies introduce structural changes and new decision-making factors, increasing complexity across tourism ecosystems.

Some studies point to the significant deficiencies in the quality data availability in many OECD countries that create a basis for the effective development of the innovation policies (Parsons et al., 2023). This fact can negatively affect the development of the decision-making tools and benchmarking systems.

There is a growing criticism that the digital technologies diminish the borders between human value and the technological services (Choi et al., 2020, 2021), primarily through depersonalised interaction (Wang et al., 2023). The introduction of artificial intelligence and the service robots also possesses an impact on increasing job uncertainty and fluctuation (Wisskirchen et al., 2017; Lu et al., 2020). The socio-economic impacts of these changes can be determined by the tourism type, the geographical factors, the political, economic and economic stability of the country, and so on. This reasons the strong specificity of the criteria valid for the defined geographical territory that will enter the construction of the decision-making tools and relevant policies.

Innovation policies in tourism, even in developed countries, are often criticized for fragmentation, slow implementation, limited scope, and weak impact, hindering sustainable tourism (Parsons et al., 2023). These issues stem from poorly developed tools for policy-making and implementation, which negatively affect sustainability efforts.

The problem of the insufficient quality of the transformation policies is also the insufficient sharing of knowledge and experience with the digital technologies in the tourism industry. Although many countries have constructed and implemented the digital transformation policies, it is clear that these processes are dominated by many actors, often with the conflicting agendas, with a strong potential to influence the business behaviour of the entities. These aspects must be taken into account when creating tools and decision-making models, where the role of expert investigations is very important.

In the studies investigating the digital transformation policies, a low proportion of the observed enterprises operating in the tourism industry is visible that can cause a significant lag in digital development, a low rate of innovative development in the tourism industry, and so on. Digital development will also be supported by a strong institutional structure, complex financing regime and similarly. This represents the additional inputs into the decision-making processes and thus, it increases their difficulty.

European tourism is shifting toward sustainability and climate responsibility, aiming to manage overtourism (Ferrer-Roca et al., 2021). Technological advances and smart tools will reshape business models, with data access becoming key for managing globalization impacts. Fuzzy models are effective for policy design, enabling scenario analysis based on quality data-exemplified by our hybrid regional evaluation model.

The study outcomes are valuable for government agencies, tourism operators, non-governmental organisations, and others involved in developing sustainable tourism policies. From an international point of view, the study outcomes are also beneficial for the other countries that focus on the implementation of the principles of sustainable development in the strategic plans for the tourism development. New business models in the future, increasing digitalisation of the processes, social innovations, big data, and the development of online trading will have an increasingly significant impact on sustainable tourism in the future. This will place increasingly high demands on monitoring and evaluation processes, forecasting trends, networking partnerships, and creating effective relationships with stakeholders. The further development of digital infrastructure and the ICT use will also create new approaches to energy monitoring, better waste management, and environmental protection. These factors will also influence the increasing complexity of the decision-making processes, risks, and uncertainty in the construction of sustainable tourism strategies (Gore et al., 2021).

Our study develops a multi-criteria hybrid model for evaluating regions in the context of sustainable tourism, which combines expert assessments of the level of sustainable development and normalized values of regions by groups of criteria. Unlike models based on fuzzy logic (Skare et al., 2024), our model reduces data redundancy, ensures adaptability to different regional conditions, and integrates socio-cultural, environmental, and economic factors. It has practical applications for assessing the effectiveness of government programs and strategic tourism planning, solving problems such as data redundancy and limited consideration of multidimensional relationships characteristic of existing approaches.

5.2. Managerial implications

To formalise the multi-criteria hybrid model, the mathematical apparatus of expert evaluation, fuzzy set theory, fuzzy logic, and multi-criteria evaluation of alternatives are used. At the same time, all settings of the multi-criteria hybrid model are tested and verified on real data. In the complex, the application of such an adequate mathematical toolkit allows for an increase in the degree of reasonableness of decision-making regarding sustainable tourism at the regional level. State authorities will be able to make proactive decisions to invest in and support tourism business in the context of sustainable tourism, increasing the environmental component and sociocultural development. Such solutions bring the era of data-driven tourism to a new level. Therefore, the developed model has an important practical value.

The proposed multi-criteria hybrid model can be effectively used by government organizations to develop sustainable tourism development strategies. It allows identifying regions with different levels of sustainability, which helps to direct public resources to support regions

with low indicators, improving their tourist attractiveness and infrastructure. In addition, the model can be integrated into monitoring systems for the effectiveness of state programs, providing objective data for assessing the impact of policies on the environmental, economic, and socio-cultural development of regions. For private organizations, the model opens opportunities for identifying promising regions for investment and developing new tourism products that meet customer needs. Tourism companies can use the results to adapt their marketing strategies, focusing on regions with the highest potential. By integrating the results of the model into their business processes, private companies can not only increase their efficiency but also demonstrate their contribution to supporting sustainable tourism, strengthening their reputation among customers and partners.

This study aims to involve the entire ecosystem of tourism business entities. Therefore, the authors of the article are not tied to specific subjects of the tourism business. Further decision-making is planned by various stakeholders who understand the importance of data management in tourism.

The advantages of the multi-criteria hybrid model for evaluating the region in the context of sustainable tourism arise from the fact that: in the model, groups of sustainable tourism criteria are easily configured, while there are no restrictions on the number of groups or criteria; the model makes it possible to understand satisfaction from the trip in the context of sustainable tourism, while using the vague logic of the psychological properties of the individual, taking into account the positive and negative aspects of the ecological component and sociocultural development; the set of linguistic conclusions of the expert level of the development of sustainable tourism in the region and the meaning of the division of gaps are easily adjusted in the process of using this model for other regions; the presented multi-criteria evaluation of the region does not require the introduction of weighting coefficients by criteria, does not use the approach of pairwise comparisons of alternatives, and can work with many regions; the multi-criteria hybrid model uses fuzzy set theory, fuzzy logic and multi-criteria evaluation; all model parameters were adjusted on real data.

5.3. Limitations and further research

A limitation of our study was the sample of respondents of the research questionnaire, as well as the use of different types of characteristic functions that are adjusted to real data. It is necessary to conduct research in other countries to have the opportunity to obtain new knowledge regarding the assessment of the level of the region in the context of sustainable tourism while expanding indicators with ecological, and sociocultural components. Nevertheless, these limitations do not affect the reliability of the developed multi-criteria hybrid model.

The reliability of the obtained results is confirmed by the justified use of theoretical mathematical tools. The rationality of the obtained ranking series of regions in the context of sustainable tourism is proven based on the advantages of the developed model. In addition, the obtained research results fully prove the formulated scientific hypothesis.

Indicators also need to be further expanded, in particular environmental ones, such as the impact of tourism on biodiversity, pollution, and the use of natural resources, as well as socio-cultural aspects, in particular the impact on local traditions, social integration, and the local economy. It is also important to expand economic indicators, assess the long-term impact of sustainable tourism on employment and infrastructure investment, and consider institutional and policy aspects, in particular the role of public and private institutions in

supporting sustainable tourism, the effectiveness of policies, and possible barriers to their implementation.

Further research on this issue can be seen in the construction of a software analytical system for evaluating sustainable regional tourism, which will allow attracting the attention of a wide audience for this research. In sum, the presented and future research will become a system of intellectual solutions for the innovative development of regions, in the context of sustainable tourism.

We will begin from the trends that are clearly defined by the impact of technological development, the digitalisation processes, and the global socio-economic and demographic changes. A strong inspiration for us are the challenges from many research studies that point to the increasing difficulty of the decision-making processes, the decision-making criteria, and the other important aspects of sustainable tourism as it is highlighted in the 5.1 subsection. Another important research topic of our further research will be a search for optimal tools based on fuzzy logic for evaluating the effectiveness of the policies introduced to manage sustainable tourism and for the development of the benchmarking indicators of sustainable tourism.

6. Conclusions

The growing complexity of the sustainable tourism processes will require the development and application of the new decision-making tools that would allow exploration the data capturing the multidimensional sectoral changes in all the organisational, process, and resource lines. The systematic building of the national and international databases and the sharing of research knowledge will also be important in an effort to support the development of the new decision-making tools and mechanisms that are necessary not only in the micro-economic environment, but also in the macro-economic environment for the creation of relevant policies. The study outcomes are very important for the entities operating in the tourism system, agencies, non-governmental organisations, creators of strategies and action plans, experts for the creation of international strategies and concepts (SDGs). Also, the study results are beneficial for the further development of the methodological and data platform.

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