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Methodological Approach in Selecting Sustainable Indicators (I_{PREGS}) and Creating an Aggregated Composite Index (AK_I) for Assessing the Sustainability of Mineral Resource Management: A Case Study of Varaždin County

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Abstract

Varaždin County is rich in mineral resources, attracting considerable investor interest in opening new exploration areas and expanding existing exploitation fields. Since the economic value of mineral resources changes with market conditions, continuous professional assessment is required. Although the proposed methodological framework is broadly applicable to mineral resource management, this case study focuses on the exploitation of construction sand and gravel deposits in Varaždin County. In this way, it addresses the sustainability challenges characteristic of quarry operations rather than large-scale mining projects. The objective of this study was to develop and test a new method for quantifying sustainability indicators in the mineral resource management (spatial, resource-related, environmental, economic, and social sustainability—I_{PREGS}) and for calculating an aggregated composite index (AK_I) using a pilot project for construction sand and gravel. The research establishes a cause–effect relationship between quantified indicators (I_{PREGS}) and the newly established aggregated composite index (AK_I). Methodologically, the study applied multivariate analysis to questionnaire data, enabling the selection, weighting, and aggregation of indicators and the design of a conceptual framework for AK_I calculation. The resulting methodology provides an instrument for monitoring and improving sustainable mineral resource management, supporting the objectives of the circular economy. The findings highlight the potential of the AK_I to reduce systemic inefficiencies, guide policy development, and offer a transparent mechanism for assessing both implementation and effectiveness. This significantly improves the current state and strengthens the basis for evidence-based economic policy-making. The case study in Varaždin County further demonstrated that the AK_I not only reproduces administrative decisions with high consistency but also clarifies how applicants should proceed in cases of partial acceptance and how policymakers can interpret conflicting outcomes across different index variants.

Keywords: aggregate composite index; I_{PREGS} indicators; mineral raw materials; sustainable management; Varaždin County

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Academic Editor: Juan M Menéndez-Aguado

Received: 22 August 2025
Revised: 3 October 2025
Accepted: 15 October 2025
Published: 20 October 2025
Corrected: 20 April 2026

Citation: Srpak, M.; Pavlović, D.; Kovač, S.; Novak Mavar, K.; Zelenika, I. Methodological Approach in Selecting Sustainable Indicators (I_{PREGS}) and Creating an Aggregated Composite Index (AK_I) for Assessing the Sustainability of Mineral Resource Management: A Case Study of Varaždin County. *Mining* **2025**, *5*, 67. https://doi.org/10.3390/mining5040067

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1. Introduction—Context and Research Objective

Croatia is not particularly rich in mineral resources. However, the sustainable management of the existing resources is of strategic importance, especially given their environmental and socio-economic impacts. In terms of the quantity of extracted mineral resources and the number of economic entities in the Republic of Croatia, the most significant activities are the extraction of architectural building stone, crushed stone aggregates, building sand and gravel, and brick clay. These resources form the basis for construction and infrastructure development but also generate significant spatial and environmental pressures. Quarrying activities, in particular, contribute to regional development but simultaneously create pressures on the environment and local communities Management of mineral resources and the overall economic benefit in mineral resource management must be based on the principles of sustainable development, which should signify balance rather than conflict. The principle of balance among economic, environmental, and socio-cultural interests is particularly emphasised in mineral resource management. Strategic decisions on the management on mineral resources must integrate knowledge about geological potential, spatial planning conditions, and restrictions related to the protection of nature, water, soil, landscape, and cultural heritage, as well as the role of socially sustainable indicators [1,2]. The framework for sustainable mineral re-source management focuses primarily on improving the efficiency of mining activities to reduce their environmental impact while considering primarily the social and economic aspects [3]. However, it is now clear that the entire life cycle of extracted mineral resources must be considered to fully assess the need for sustainable mineral resource management in light of future demand driven by population growth and economic development [4,5].

Although no universally accepted framework exists for quantifying sustainability in the mineral resource sector, numerous approaches to constructing and weighting indicators are available. Reviews of sustainability assessment tools [6–8] and international initiatives [9] highlight the diversity of methods. Recent applications also demonstrate the growing use of sustainability assessment in the mineral sector, for example in Russia [10] and in global mineral resource studies [11]. Other methodological contributions have focused on specific weighting approaches such as entropy-based weighting [12], multi-criteria frameworks [13], and the analytic hierarchy process [14]. These approaches demonstrate the potential of composite indices to synthesise complex information, though their applicability in region-specific contexts, such as Croatia, remains underexplored. Rapid economic and technological changes, globalisation, and aspects of post-industrial development have significantly altered the role and significance of mineral resources in the modern economy and civilization since the 19th century. All these factors have led to changes, but not to a reduction in the role and importance of mineral resources in the modern economy. Concerns about environmental, economic, technological, and spatial conditions, as well as cultural changes, have led to increased public awareness and enhanced environmental preservation efforts, resulting in heightened sensitivity of the general public and the scientific community to the exploration and exploitation of mineral resources. The environmental and spatial planning issues related to mineral resource exploration and exploitation in Varaždin County are extensive. Natural resources are consumed, numerous surface mines alter the landscape (soil), climate, groundwater, and surface water regimes are affected, dust and gases pollute the atmosphere, the noise associated with mining activities disrupts wildlife, while removal of resources can lead to the destruction of existing biocenoses, particularly in forests. Given this environmental sensitivity, environmental protection has become a robust control mechanism, and environmental indicators are essential tools that provide information on the impact of interventions on the environment, to be quantified at the ecosystem level [15,16]. The analysis of social conditions during the life cycle of mineral

resource management focuses on several key functions, including economic well-being, health and safety, and public opinion. Comparing these functions makes it possible to compare different process chains and quantify variations in social impacts, in order to make them quantitatively visible and comparable [17,18].

The area of Varaždin County is rich in mineral resources (building sand and gravel, crushed stone, and brick clay), which has led to significant interest from investors in opening new exploration areas and developing existing exploitation fields. However, the Mining-Geological Study of Varaždin County [19], states that the current reserves of building sand and gravel, crushed stone aggregates, and brick clay are sufficient until 2045 and 2053, respectively, to meet the demand for building materials in planning future infrastructure projects and for the processing industry. This situation underlines the importance of developing robust indicators to evaluate sustainability dimensions spatial, resource-related, environmental, economic, and social, when considering potential future projects.

The aim of this study is to develop and compare alternative methods for weighting and aggregating sustainability indicators within the (I_{PREGS}) framework, leading to the construction of an Aggregated Composite Index (AK_I) [20,21]. This approach is applied to the case of Varaždin County, with the broader objective of informing future management policies and supporting the transition towards a circular economy in mineral resource management. The primary objective is to evaluate how methodological choices influence sustainability assessment outcomes. In doing so, the paper contributes to methodological debates on composite indicators and addresses the practical needs of decision-makers responsible for permitting and managing quarry development projects.

2. Methodological Approach to Defining and Selecting Key Sustainability Indicators (I_{PREGS})

Spatial, resource-related, environmental, economic, and socio-sustainable sustainability call for the development of new models to effectively manage mineral resources in a sustainable way. This is especially relevant today, as the increasing influence of the global economy affects all stakeholders in society. The mining sector in particular has an unprecedented opportunity to mobilise social, physical, technological, and financial resources in support of the Sustainable Development Goals [22]. In practical terms, indicators serve as essential methodological tools to explore, analyse, and assess the impacts and relationships among different phenomena They help to simplify the complexity of spatial and sustainability issues into a manageable number of relevant variables. Therefore, within the concept of sustainable development, indicators (measurable values) track the changes and the achievement of goals from all sectoral policies and strategies, providing qualitative and quantitative information in a simple and clear way. Črnjar & Črnjar [23] emphasised the necessity for indicators to be specific, measurable, usable, flexible, accessible, and cost-effective. During the selection of sustainability indicators, particular attention is given to the characteristics embodied within their respective sub-indicators. With these principles in mind, our study adopts a holistic approach by analysing the influence of all indicators that directly or indirectly affect sustainable mineral resource management, with a focus on the specific territorial context Consequently, five key sustainability indicators were selected: spatial, resource-related, environmental, economic, and socio-sustainable, collectively referred to as (I_{PREGS}) (Figure 1).

The selection of these five key indicators (I_{PREGS}) was guided by their direct relevance to sustainable mineral resource management, their consistency with internationally recognised sustainability frameworks (e.g., UN SDGs, EU environmental standards), and their applicability within the regional context. Each indicator is associated with measurable sub-indicators: for instance, spatial indicators are expressed through demographic

and settlement data (quantitative), resource indicators through geological reserves and extraction volumes (quantitative), ecological indicators through biodiversity and emission levels (quantitative/qualitative), economic indicators through revenues and investment flows (quantitative), and social indicators through stakeholder satisfaction and legal compliance (qualitative/ordinal). This framework ensures both methodological clarity and comparability across all dimensions of sustainability.

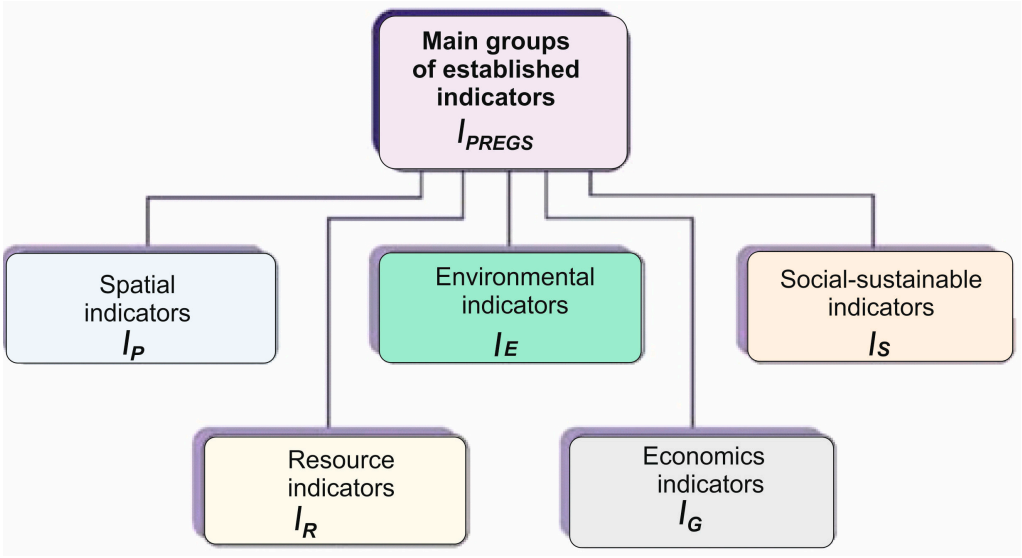


Figure 1. Identified main groups of indicators.

This diagram displays the key groups of indicators that collectively enable a complex and integrated analysis of sustainability in mineral resource management. These indicators cover spatial, resource, environmental, economic, and social dimensions, ensuring a comprehensive approach to assessing the impacts of mining activities across multiple facets of sustainable development. The figure emphasises the necessity of their synergistic use, highlighting the interconnections and complementarity fundamental to forming effective management strategies. A practical example from the Varaždin County case study illustrates how the systematic application of such a multidimensional indicator set can support balancing economic benefits with environmental and social sustainability, thereby aiding decision-making aligned with the principles of the circular economy. This approach provides a methodological framework for transparent evaluation and governance of the complex effects of mineral resource exploitation, and the methods employed within the system can serve as a basis for developing and adapting policies aimed at the long-term preservation of natural resources and maximising societal benefits.

The selection of the most significant sub-indicators (initiatives), 50 in total, was based on a review of available literature, including scientific research papers addressing the selection and implementation of various initiatives, along with their subordinate activities to promote sustainable management of mineral resources. Although the initial questionnaire analysis covered 50 sub-indicators collected from 136 respondents, only 25 are presented in this study. This subset was selected based on statistical significance, representativeness, and dominance within each indicator group, thus highlighting the most relevant and impactful sub-indicators. Such focused selection improves clarity and interpretability of results and enhances their practical applicability in policy-making and strategic planning. Moreover, the methodological foundations and criteria for selecting indicators are well-supported by relevant research. Villas Bôas et al. (2005) [24] provided a comprehensive review of sustainability indicators for the mineral extraction industries, emphasising the need for a comprehensive set of indicators that address economic, social, and environmental dimen-

sions. Fuentes et al. (2021) [25] contributed by classifying environmental sustainability indicators specific to copper mining and processing, highlighting the importance of context-specific frameworks. Additionally, the United Nations Development Programme (UNDP) (2018) [26] offers authoritative guidelines on sustainable mining management, integrating social and environmental priorities within policy frameworks. Bui et al. (2017) [27] proposed an indicator-based sustainability assessment framework tailored for the mining sector within APEC economies, stressing the necessity of regional customisation. Collectively, these studies underline the importance of integrative, multidisciplinary approaches to developing effective sustainability indicator systems for mineral resource management. This approach aligns with Pavlović's [28] study on the optimization of the natural gas system of the Republic of Croatia through the integration of liquefied natural gas terminals, underlining the crucial role of strategic planning in shaping the country's energy policy. The criteria for forming I_{PREGS} in the questionnaire are the relationships between the respective characteristics and the subject of the sub-indicator (initiative) being evaluated in this case, the management of mineral resources. In the context of contributing to research and discovering regularities, as well as recognising functional cause-effect relationships, considering the level of measurement, comparison of indicators and criteria, and prediction and guidance, this scientific work will define the value of the indicators (I_{PREGS}) and criteria for all individual indicators through research.

2.1. Spatial Indicators

The interdisciplinary approach to research in the application of spatial indicators arises from the close link between spatial planning and the resource, economic, environmental, and social dimensions of planning, seeking to achieve an integrated approach to spatial planning in relation to the exploration and exploitation of mineral resources. By selecting spatial indicators, the existing state resulting from the long-term use and exploitation of mineral resources will be determined. The sensitivity of the area will be recognised, as well as the mutual impacts of planned/existing exploration areas and exploitation fields, along with unrealized interventions, all with the aim of sustainable development of the mining industry and sustainable management.

By Analysing spatial planning documentation, and considering the area of interest—the Pilot project for construction sand and gravel, spatial indicators determined in the questionnaire will be evaluated in more detail:

- General indicators of development trends (demographic and socio-economic structure),
- Characteristics and development of settlements (settlement system, distribution, density, population),
- Areas designated for the exploration and exploitation of mineral resources,
- Hospitality and tourism use (sports and recreation),
- Economic use (production, business),
- Transportation infrastructure (road, rail, air transport)
- Energy infrastructure (gas pipelines, high voltage power lines 110 kV, 35 kV),
- Waste management facilities,
- Use of natural resources (agriculture, forestry, water).

2.2. Resource Indicators

Resource bases and mining-geological studies are documents used to identify deposits, estimate reserves, and assess the potential for the exploitation of all mineral resources. Aldakhil et al. [29] emphasised that several indicators drive the exploitation of mineral resources, and the results show that population density and forested areas are causative indicators influencing resource exploitation. Taking this further, Hussain et al. [30] found

that the depletion of natural resource indicators leads to an increase in carbon emissions and energy consumption, negatively impacting resource conservation.

For the area of interest, the resource indicators determined in the questionnaire were evaluated in more detail:

- Geological criteria (geological structure indicating the possibility of mineral resource deposits in barren areas)—basic geological map at a scale of 1:100,000,
- Resource potentials (for all types of mineral resources),
- Balance of mineral resource reserves,
- Trend in balance of mineral resource reserves,
- Trend in non-balance of mineral resource reserves,
- Trend in exploitation reserves of mineral resources,
- Trend in quantities of mineral resources extracted,
- Resource protection and rational use,
- Area reclamation,
- Recycling of used mineral resources.

2.3. Ecological Indicators

Štrbac and colleagues [31] categorised environmental indicators as relating to the atmosphere, hydrosphere, soil, and biological diversity. Mining activities have a certain negative impact on the environment, making environmental indicators crucial as direct sources of information for decision-making. Their purpose is to influence decisions to reduce decision to reduce negative environmental impacts and help establish ecosystem balance. There are several criteria for selecting environmental indicators, and in this study, the focus is on indicators with direct or indirect impact on the exploration and exploitation of mineral resources. These indicators include:

- Protected area (Regional Park Mura—Drava, Nature Park, Forest Park, significant landscape),
- Ecological network (Natura 2000),
- Seismic features,
- Communication with the interested public,
- Pedological characteristics,
- Climate,
- Noise (heavy machinery operation, transportation, mining),
- Impact on flora,
- Impact on fauna,
- Environmental risk assessment.

2.4. Economic Indicators

Economic indicators encompass new models of education and sustainable business practices to achieve a competitive advantage through the optimal use and increased productivity of available resources. As a result, many mining companies today rely on economic growth and development. Porter and van der Linde [32] concluded that economic sustainability provides dual benefits: for the economy and the environment, highlighting significant untapped opportunities in developing technological innovations that both preserve the environment and enhance economic activity. The mining sector and related processing activities in Varaždin County form an important part of the economy, so the following indicators have been defined based on the Questionnaire:

- Number of entrepreneurs in the mining/processing sector,
- Total revenues/expenditures,
- Amount of taxes and fees for exploitation,
- Profits from mining/processing activities,

- Losses from mining or processing activities,
- Investments in mining or processing activities,
- Significance of exploration/exploitation for the local economy,
- Exports (revenue),
- Salaries in these sectoral activities,
- General social benefit for the Republic of Croatia/County/City/Municipality.

2.5. Social Sustainability Indicators

In an era of rapid globalisation and industrialisation, economic entities/mining companies are vital contributors to social development. Socially sustainable economic development indicators are based on cost distribution, administrative users, employees, business partners, assistance to the local community, and development promotion. According to Kotler and Lee [33], corporate social responsibility represents a company's ability to care for the well-being of the community and society. Indicators determining the competitiveness of the mining industry are strongly influenced by global processes, resulting in conflicts at all levels of spatial, resource, economic, ecological, and social sustainability actions. The mining sector and related processing activities in Varaždin County form an essential segment of the economy. Based on the questionnaire, the following indicators have been defined:

- Cost distribution,
- Administrative users (Ministry of Economy, Mining Administration, economic departments in counties, cities, municipalities, authorised representatives and users),
- Public (interested parties, the environment, associations),
- Authorised companies (authorised individuals preparing reports on mineral resource reserves, main mining projects, environmental impact studies),
- Legal regulations,
- Protection of the rights of all stakeholders,
- Satisfaction of the local population,
- Satisfaction of authorised persons,
- Maximum adaptation of exploitation to environmental conditions and social interests,
- Development promotion (communication, education, partnership).

Although this study primarily relies on expert judgment and statistical methods for the selection and weighting of indicators within the I_{PREGS} framework, the development of a new model (AK_I) provides a tool for monitoring and improving sustainable mineral resource management. Alongside the applied approach, it is important to acknowledge other advanced weighting methodologies, such as the Analytic Hierarchy Process (AHP), the entropy method, Principal Component Analysis (PCA), and fuzzy logic. Although these methods were not applied in this study, their recognition demonstrates openness to future methodological improvements aimed at enhancing the precision and relevance of composite sustainability indices. Each of these methodologies offers specific advantages: AHP supports hierarchical evaluation of expert assessments, the entropy method provides objective weights based on data dispersion, PCA reduces dimensionality, while fuzzy logic allows greater flexibility in addressing imprecise and uncertain data. As an extension of classical Boolean logic, fuzzy logic permits the expression of varying degrees of membership and uncertainty. Unlike binary logic, where variables can only take values of 0 or 1, fuzzy logic accommodates continuous values in the range between 0 and 1, thereby offering a more realistic framework for modelling uncertainty and subjective judgments in decision-making. Advanced methodologies such as fuzzy logic modelling also offer promising opportunities for managing imprecise, uncertain, and qualitative data types frequently encountered in sustainability assessments. While not implemented in this study, their recognition underscores a forward-looking perspective and openness toward

methodological advancements aimed at improving the accuracy and policy relevance of composite sustainability indices. In selecting sustainability indicators in this study, emphasis was placed on ensuring their precision, measurability, practicality, adaptability, accessibility, and economic justification [1]. For this reason, the design and projection of future indicators were approached holistically, by analysing the influence of all factors that directly or indirectly shape sustainable mineral resource management. The methodological decisions underpinning this work were guided by the dual objectives of transparency and practical applicability, with particular attention to clear communication with stakeholders. In this way, the constructed indices capture the complex interplay among spatial, resource-related, environmental, economic, and social dimensions, providing a robust foundation for decision-making aligned with the specific context of Varaždin County.

3. Definition and Formation of the Aggregated Composite Index

Creating a new model (AK_I), as a tool for monitoring and improving the system of sustainable mineral resource management in the context of achieving green GDP and a circular economy in the development of Varaždin County's economy, should be integrated into a broader framework of development and economic policy. This framework should include integrated legal and targeted implementation measures and provide mechanisms for monitoring the effectiveness of implementation. In practice, composite indices are often used as indicators to identify trends when analysing phenomena and can be useful tools in setting policy priorities by monitoring the implementation of measures. Ideally, multidimensional concepts that cannot be measured by a single indicator, such as competitiveness, industrialisation, sustainability, integration of the single market, and a knowledge-based society, should be measured. Different aspects of research on this topic point to its complexity and multidimensionality, with certain problems related to the selection of representative indicators and their meaning structures observed in the literature reviewed and the practices of individual countries [34]. The indicators and sub-indicators (initiatives) were selected based on their analytical significance, representativeness, measurability, and interconnections based on empirical analyses, theoretical assumptions, a survey conducted, expert intuition, informativeness, and pragmatism in defining real (practical) value. Poorly constructed or misinterpreted composite indices can lead to misguided management strategies. Therefore, the validation of such models is of great importance, as these models cannot be validated in terms of proving their correctness [35]. The validity of the indicators is therefore based on their quality for the intended use and acceptance by experts [36]. According to Saisana and Saltelli [37], a model can be accepted and validated if it passes tests that assess its ability to explain or predict convincingly and parsimoniously. Perišić and Wagner [38], state that composite indices must be developed based on the best parameters, be transparent, documented, and validated using appropriate methods for uncertainty and sensitivity analysis.

In constructing the aggregated composite index in our research, the aim was to derive a single number (AK_I) from a large number of input data (sub-indicators) divided into several groups (key indicators) that consistently and reliably represent and express the overall variability of the input data. Therefore, it is of utmost importance to communicate all the steps leading to the creation of the aggregated composite index with experts who will use such an index in order to eliminate potential sources of uncertainty. In developing the aggregated composite index in this research, the Methodology for Developing Composite Indicators [9] was consulted as the primary source of information (Figure 2).

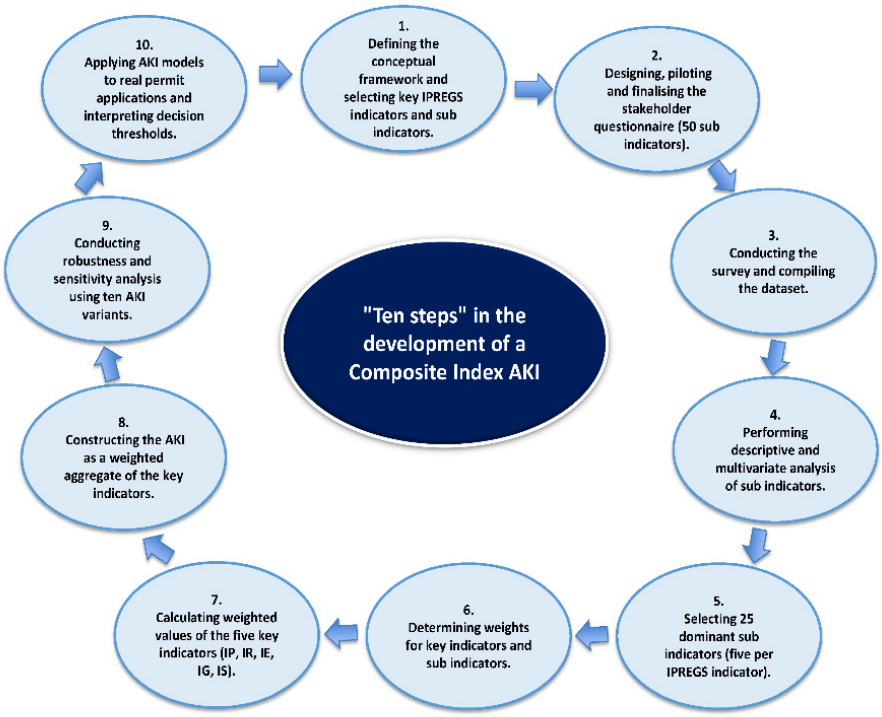


Figure 2. Composite index formation procedure (10 steps).

Social Sustainability Indicators

While selecting participants and addressing potential difficulties in creating the survey questionnaire and conducting the primary research, a pilot study was conducted to test the questionnaire with a sample of seven participants/employees of the Spatial Planning Institute of Varaždin County. Based on the results of the pilot study, the questionnaire was finalised, and the participants, or respondents, who constitute the research sample, were identified as follows:

- Employees of the Spatial Planning Institutes in four neighbouring counties (Varaždin, Međimurje, Koprivnica–Križevci, Krapina–Zagorje),
- Environmental associations in Varaždin County,
- Local administrative units bordering Varaždin County (Međimurje, Koprivnica–Križevci, Krapina–Zagorje counties),
- Mining concessionaires/authorised individuals engaged in mining activities in the four counties (Varaždin, Međimurje, Koprivnica–Križevci, Krapina–Zagorje),
- Legal entities with consent to perform environmental protection-related tasks.

The questionnaire was sent to 254 addresses between 1 September 2021, and 6 December 2022 according to the research plan. In this empirical research, participants were asked to select and tick the priority level influences of key indicators that best reflected their opinion (within the groups of spatial, resource, environmental, economic, and socio- sustainable indicators). Each of the five components of the model (subsequently used in the development of the aggregated composite index—indicators) was described by sub-indicators. Sub-indicators are variables whose values are determined according to the procedure described in the following subsections. A Likert scale with five levels was used in the management of mineral resources [39].

Through statistical analysis of the results, including multivariate analysis, weighting factors and data aggregation were applied, and a sensitivity test of the results to changes in weighting factors was conducted. Individual indicators or sub-indicators were analysed in more detail regarding their impact on the overall aggregated composite index, and the

results were linked to other independent variables. After applying detailed analytical methods and reviewing available data from the literature in the field, 25 different indicators were randomly selected within the five chosen categories (spatial, resource, environmental, economic, and socio-sustainable). It was found that these indicators are important determinants for the construction of the aggregated composite index. After their definition and mathematical quantification (statistical interdependencies), the values of the weighting factors were determined. When determining the values of the weighting factors for the observed indicators, it was assumed that all weighting factor values belong to the elements of an explicit (classical) set, with their values falling within the real value interval [0, 1]. Additionally, the sum of these weighting factors must equal [1,39]. The results of the survey conducted provided relevant data indicating that the measurement process is feasible, as all relevant indicators were included in the model. Each indicator was assigned an appropriate weighting factor, and their total sum equalled (Table 1).

Table 1. Display of weights for I_{PREGS} [40].

Key Indicator Mark	Indicator Name	Weighted Value
Ip-Is	spatial	0.15
Ir	resource	0.25
Ien	environmental	0.30
Ie	economic	0.10
Is	social- sustainable	0.20

Table 1 shows the weighting factors assigned to the five key sustainability indicators within the I_{PREGS} framework. For clarity, these values are also presented in Figure 3 as a bar chart. The graphical representation illustrates the relative importance of each indicator in shaping the composite index and complements the tabular presentation. Both formats enable a clear comparison of the contribution of each sustainability dimension to the overall framework.

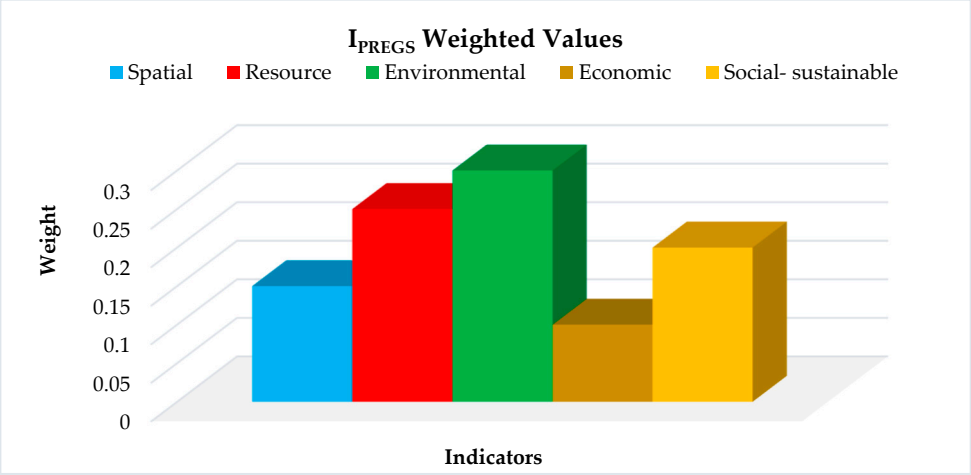


Figure 3. Weight Distribution of Key Sustainability Indicators (I_{PREGS}).

Based on the data from the Questionnaire completed by all stakeholders for the selected five key indicators (spatial, resource-based, environmental, economic, socio-sustainable), five additional sub-indicators were ranked and selected for each indicator, totalling 25. The selection was based on the dominant level of factors and the assigned percentage share resulting from the survey processing) (Table 2).

Table 2. Selected Key Indicators and Sub-Indicators [40].

Key Indicator Mark	Indicator Name	Weighted Value
Spatial Indicators —I_P	Areas designated for exploration and exploitation of mineral resources	PP1
	Characteristics and development of settlements (settlement system, layout, density, population)	PP2
	Transport infrastructure (road, railway, air transport)	PP3
	Energy Infrastructure (gas pipelines, high-voltage power lines 110 kV, 35 kV)	PP4
	Utilization of Natural Resources (agriculture, forestry, water)	PP5
Resource Indicators —IR	Geological criteria (geological structure of deposits- Basic geological map scale 1:100,000)	RP1
	Resource potentials	RP2
	Balance of mineral resources reserves	RP3
	Resource protection and sustainable utilization	RP4
	Space remediation	RP5
Ecological Indicators —IE	Space protection (Mura-Drava Regional Park, Nature Park, Forest Park, significant landscape	EP1
	Ecological network-Natura 2000	EP2
	Communication with the public	EP3
	Noise (heavy machinery operation, transportation, mining)	EP4
	Impact on flora	EP5
Economic Indicators —IG	Investments in mining/processing activities	GP1
	Losses in mining/processing activities by sector	GP2
	Significance of research/exploitation for the local economy	GP3
	Export (Revenue)	GP4
	General Social Benefit Republic of Croatia/County/City/Municipality	GP5
Social Sustainability Indicators —IS	Licensee Satisfaction	SP1
	Legal Regulation	SP2
	Protection of the rights of all stakeholders	SP3
	Satisfaction of the local population	SP4
	Promotion of development (communication, education, partnership)	SP5

The questionnaire was distributed to a representative group of stakeholders, including local government officials, experts from the mining and processing industries, environmental specialists, academic researchers, and civil society representatives. Prior to distribution, the purpose of the survey and the relevance of the I_{PREGS} framework were clearly explained, and respondents were assured of confidentiality. The survey was administered in both electronic and paper formats during stakeholder meetings and via direct communication channels. A total of 47 completed questionnaires were collected, representing a response rate of 78%. The sample included all major stakeholder groups relevant to sustainable mineral resource management, which ensured both representativeness and reliability in the ranking and selection of sub-indicators [40].

Several sub-indicators included in the analysis, which are qualitative and complex in nature (such as "characteristics and development of settlements," "noise," "legal regulations," "drinking water protection," "access to infrastructure facilities," "Natura 2000 ecological network," "work safety and health protection," "presence of cultural heritage"), were assessed based on expertise and experience of relevant specialists. Evaluations were conducted using a structured approach to collecting expert opinions from fields including spatial planning, environmental protection, mining industry, and legal regulation. A hierarchical procedure was applied, in which experts rated individual indicators based on predefined criteria of importance and impact, and the indicators were weighted according to their significance within the context of sustainable mineral resource management.

In addition to the hierarchical approach, Delphi surveys and structured expert discussions, known as moderated group discussions, were used as supplementary techniques for gathering and unifying expert opinions. The Delphi method involved several rounds of anonymous questionnaires aimed at reaching a consensus an approach that significantly reduces subjectivity and increases the reliability of assessments. Moderated group discussions enabled open and detailed exchanges of views among experts from various fields, contributing to the clarification of ambiguities and the resolution of inconsistencies regarding specific indicators.

This combined and systematic approach ensured that complex and qualitative components were evaluated transparently and rigorously, creating a consensus-based and reliable basis for further quantitative analysis aimed at enhancing sustainable mineral resource management.

Since the sub-indicators are grouped into five categories: spatial, resource-related, environmental, economic, and socio-sustainable, with an equal number of sub-indicators in each category, the top five dominant sub-indicators were selected from each category. This selection was based on the sub-indicators' highest dominant value (mode), and in cases where multiple sub-indicators had the same mode, preference was given to the sub-indicator with the higher arithmetic mean. The aggregated composite index should correspond to the components and attributes of the general theoretical conceptual model and encompass the findings of the qualitative comparative analysis conducted.

Descriptive statistical analysis was used to calculate the mean, mode, median, standard deviation, and coefficient of variation for $n = 25$ (five categories of indicators x five sub- indicators). Individual indicators or sub-indicators were analysed in more detail in terms of their impact on the aggregated composite index, and the results were linked to other independent indicators. Table 3 provides descriptive indicators calculated for the given frequencies. Statistical analysis was conducted for each of the 50 specified sub-indicators in a sample of 136 respondents. The statistical analysis includes calculations of the measures of central tendency (mean, mode, and median), the measures of dispersion (standard deviation, variance, and coefficient of variation), and the measures of skewness (skewness coefficient).

Table 3. Measures of central tendency and measures of variation for selected sub-indicators.

Sub Indicator	Meana (A.M.)	Mode (M)	Median (m)	Standard Deviation (σ)
PP1	3.7	5	4	1.36
PP2	2.7	3	3	1.24
PP3	3.6	4	4	1.35
PP4	3.5	5	4	1.42
PP5	3.8	5	4	1.43
RP1	3.6	5	4	1.38
RP2	4.0	5	4	1.12
RP3	3.3	3	3	1.27
RP4	4.0	5	5	1.22
RP5	4.2	5	5	1.18
EP1	4.3	5	5	0.93
EP2	4.2	5	4	0.92
EP3	3.6	5	4	1.30
EP4	3.9	5	4	1.14
EP5	3.6	4	4	1.18
GP1	3.1	3	3	1.24
GP2	3.1	3	3	1.15
GP3	3.5	4	4	1.25
GP4	3.6	5	4	1.33
GP5	3.7	5	4	1.35
SP1	3.4	4	4	1.29
SP2	4.2	5	5	1.11
SP3	3.4	4	4	1.15
SP4	3.5	5	4	1.38
SP5	3.5	5	4	1.33

Note: Only central tendency (mean, median) and standard deviation are shown for clarity. Additional measures (variance, coefficient of variation, skewness) are available in Appendix A.

The mode is very important in this assessment because it represents the most dominant or typical value, reflecting the sub-indicator chosen by the majority of respondents. However, Table 3 (Appendix A. Full statistical measures for selected sub-indicators) shows several sub-indicators with the same mode. Therefore, the mean is also considered as a relevant parameter for determining the importance of sub-indicators. The skewness coefficient is important because if its value is negative and larger in absolute terms, this indicates data asymmetry towards higher values, which means a greater concentration of data on the higher side. In such cases, these sub-indicators are considered highly important. Based on this analysis, decisions were made regarding the distribution of importance across the sub-indicators, which helped to determine the weighting and ultimately the formation of the aggregated composite index. Among the five key indicators, there are only slight differences in relationships to sustainable mineral resource management in the Varaždin County area. The key indicator with the highest mean and mode value is the environmental indicator (I_E), followed by the resource indicator (I_R), then the social-sustainability indicator (I_S), the spatial indicator (I_P), and finally, the economic indicator (I_G). All five key indicators show very low values for measures of dispersion (standard deviations and coefficients of variation), further confirming that the data obtained from the survey is consistent, and does not show any significant deviations. Table 4 provides an overview of the main measures of central tendency (arithmetic mean, mode, median), together with the standard deviation and coefficient of variation for the five key sustainability indicators (I_{PREGS}).

Table 4. Table of mean, mode, median, standard deviation, and coefficient of variation for selected indicators.

Indicator	Mean	Mode	Median	Standard Deviation	Coefficient of Variation
I_P	17.27	22	19	0.4297	0.02488
I_R	19.14	23	21	0.3644	0.01903
I_E	19.58	24	21	0.3239	0.01654
I_G	16.94	20	18	0.2625	0.0155
I_S	18.02	23	21	0.3179	0.01764

These values offer a reliable insight into the structure of stakeholder responses and the degree of their mutual consistency. The relatively low values of the measures of dispersion indicate a high level of agreement among respondents, confirming both the consistency and credibility of the conducted survey. Figure 4 illustrates the arithmetic means and mode values for the five indicators, enabling a clearer and faster comparison of their relative importance.

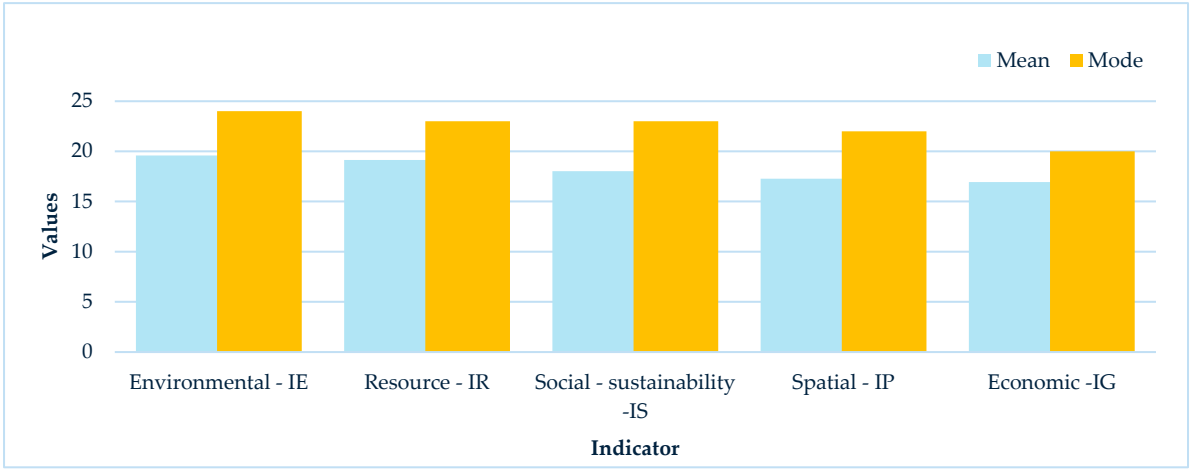


Figure 4. Arithmetic mean and mode values of the five key sustainability indicators (I_{PREGS}: I_E, I_R, I_S, I_P, I_G).

The results show that the environmental indicator (I_E) reaches the highest values, reflecting the dominant perception of the importance of environmental aspects in sustainable mineral resource management. It is followed by the resource indicator (I_R), which emphasizes the importance of rational use and preservation of reserves. The social sustainability indicator (I_S) and the spatial indicator (I_P) occupy intermediate positions, while the economic indicator (I_G) appears as the least pronounced in stakeholder perceptions. This distribution clearly demonstrates that stakeholders primarily associate sustainable mineral resource management in Varaždin County with environmental protection and efficient resource use, while social and spatial factors play complementary roles, and economic aspects are perceived as less decisive. The graphical representation in Figure 4. visually confirms these relationships, facilitates their interpretation, and supports the next steps in constructing the composite sustainability index.

4. Formation of Aggregated Composite Index (AK_I)

It is defined as the sum of all key indicators with assigned weights (weighting coefficients), as follows:

$$AK_I = 0.\,15 \times I_P + 0.\,25 \times I_R + 0.\,30 \times I_E + 0.\,10 \times I_G + 0.\,20 \times I_S$$

where I_P, I_R, I_E, I_G, and I_S are the calculated values of the key indicators: spatial indicator, resource indicator, environmental indicator, economic indicator, and social-sustainable indicator for the specific case to be examined using the aggregated composite index. The values of the key indicators I_P, I_R, I_E, I_G, and I_S are calculated from ratings in the form of percentages for each of the 25 selected sub-indicators (PP1, SP5) in the following way:

- IP = 0.25·PP1 + 0.10·PP2 + 0.20·PP3 + 0.15·PP4 + 0.30·PP5
- IR = 0.15·RP1 + 0.25·RP2 + 0.10·RP3 + 0.20·RP4 + 0.30·RP5
- IE = 0.30·EP1 + 0.25·EP2 + 0.15·EP3 + 0.20·EP4 + 0.10·EP5
- IG = 0.15·GP1 + 0.10·GP2 + 0.20·GP3 + 0.25·GP4 + 0.30·GP5
- IS = 0.10·SP1 + 0.30·SP2 + 0.15·SP3 + 0.25·SP4 + 0.20·SP5

The weighting coefficients for the sub-indicators are equal to those for the key indicators, and the allocation was performed by ranking the sub-indicators based on mode, arithmetic mean, and coefficient of asymmetry. It is evident that the weights of the key indicators are the same as the weights in AK_I, but they are assigned differently (depending on the ranking of the importance of sub-indicators based on mode, arithmetic mean, and coefficient of asymmetry of sub-indicators). Therefore, the expression of AK_I using all 25 sub-indicators is as follows:

AKI = 0.15· (0.25·PP1+0.10·PP2+0.20·PP3+0.15·PP4+0.30·PP5)+
+0.25·(0.15·RP1+0.25·RP2+0.10·RP3+0.20·RP4+0.30·RP5)+
+0.30·(0.30·EP1+0.25·EP2+0.15·EP3+0.20·EP4+0.10·EP5)+
+0.10·(0.15·GP1+0.10·GP2+0.20·GP3+0.25·GP4+0.30·GP5)+
+0.20·(0.10·SP1+0.30·SP2+0.15·SP3+0.25·SP4+0.20·SP5)

Ratings for the sub-indicators are assigned by the evaluator based on their experience using the Form for Calculating the Aggregate Composite Index, as presented in Table 5.

Table 5. Weight coefficients assigned to sub-indicators within the I_{PREGS} framework.

Sub-Indicator	Weight Coefficient (W)	Key Indicator
PP1	0.25	$I_P = 0.25 \cdot PP1 + 0.10 \cdot PP2 + 0.20 \cdot PP3 + 0.15 \cdot PP4 + 0.30 \cdot PP5$
PP2	0.10	
PP3	0.20	
PP4	0.15	
PP5	0.30	
RP1	0.15	$I_R = 0.15 \cdot RP1 + 0.25 \cdot RP2 + 0.10 \cdot RP3 + 0.20 \cdot RP4 + 0.30 \cdot RP5$
RP2	0.25	
RP3	0.10	
RP4	0.20	
RP5	0.30	
EP1	0.30	$I_E = 0.30 \cdot EP1 + 0.25 \cdot EP2 + 0.15 \cdot EP3 + 0.20 \cdot EP4 + 0.10 \cdot EP5$
EP2	0.25	
EP3	0.15	
EP4	0.20	
EP5	0.10	
GP1	0.15	$I_G = 0.15 \cdot GP1 + 0.10 \cdot GP2 + 0.20 \cdot GP3 + 0.25 \cdot GP4 + 0.30 \cdot GP5$
GP2	0.10	
GP3	0.20	
GP4	0.25	
GP5	0.30	
SP1	0.10	$I_S = 0.10 \cdot SP1 + 0.30 \cdot SP2 + 0.15 \cdot SP3 + 0.25 \cdot SP4 + 0.20 \cdot SP5$
SP2	0.30	
SP3	0.15	
SP4	0.25	
SP5	0.20	

Table 5 summarises the distribution of weights across all 25 sub-indicators. As shown, the weights are not evenly distributed but reflect the relative importance assigned during the evaluation process. For example, within the environmental indicator (IE), EP1 has the highest weight (0.30), underscoring its priority in sustainability assessment, while EP5 is less influential (0.10) [40]. This differentiation reflects the perceptions of stakeholders and highlights the multidimensional nature of sustainable mineral resource management.

Figure 5 illustrates the distribution of weight coefficients assigned to the 25 selected sub-indicators, grouped under the five key sustainability dimensions: spatial (I_P), resource (I_R), environmental (I_E), economic (I_G), and social-sustainable (I_S).

The results clearly indicate that the weights are not distributed evenly but instead reflect the relative importance of sub-indicators as determined through the stakeholder survey and subsequent statistical ranking. Sub-indicators such as PP5, RP5, EP1, GP5, and SP2 were assigned the highest weight (0.30), underscoring their central role in shaping sustainability assessments within their respective categories. In contrast, PP2, RP3, EP5, GP2, and SP1 received the lowest weight (0.10), pointing to their more limited contribution to the formation of the composite index. This graphical representation complements the tabular data presented in Table 5 by offering a clearer and more intuitive overview of the relative influence of each sub-indicator. In doing so, it enhances the transparency of the weighting process and facilitates a better understanding of how individual elements contribute to the overall sustainability assessment.

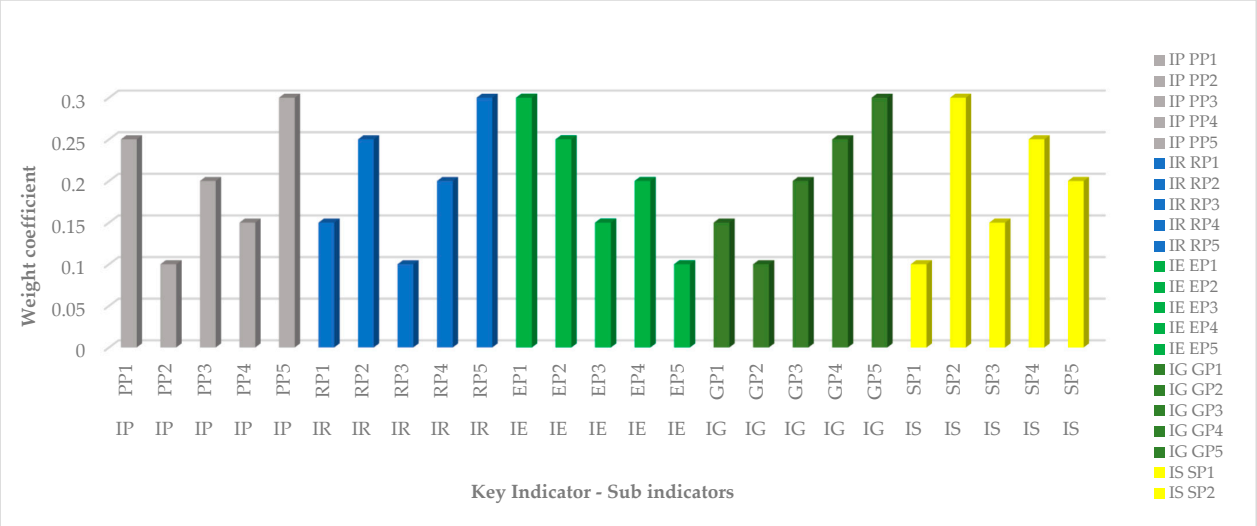


Figure 5. Weight coefficients of sub-indicators within the I_{PREGS} framework.

The Aggregate Composite Index (AK_I) is expressed as a percentage, which allows the results to be directly linked to decision-making categories. To operationalise this concept, clear thresholds were defined to determine whether a particular case is considered unsuitable, conditionally feasible, or fully feasible for exploitation. The boundaries are presented in Table 6.

Table 6. Decision thresholds for the Aggregate Composite Index (AK_I).

AKI Value (%)	Decision Category
0–30%	Not recommended
30–70%	Partial exploitation
70–100%	Full exploitation

Table 6 provides a structured classification of AKI values and enables their translation into categories that are both transparent and practical. This allows results to be clearly communicated to decision-makers at different levels, including policymakers, industry representatives to local communities directly affected by resource management decisions. To further enhance readability, Figure 6 presents the same information in the form of a stacked bar chart.

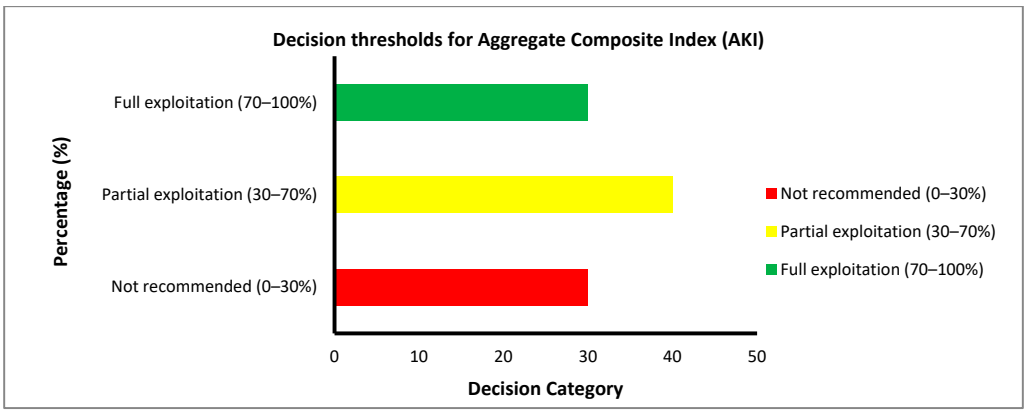


Figure 6. Decision thresholds of the Aggregate Composite Index (AK_I).

Figure 6 illustrates the three decision categories derived from AKI values: "not recommended" (0–30%), "partial exploitation" (30–70%), and "full exploitation" (70–100%). The visual form complements Table 6, allowing for a quicker understanding of the decision boundaries.

5. Case Study: Application of the Aggregated Composite Index (AK_I) in Varaždin County

- As no standardised methodology currently exists for validating an aggregated composite index, this study draws upon several previous applications for the exploitation of construction sand and gravel in Varaždin County. The empirical basis comprised actual applications submitted between 2019 and 2022, which served as test cases for different variations in the AK_I. All analysed cases referred to mineral resource exploitation sites in Varaždin County, comprising one fully approved (Case 1), one partially approved (Case 2), and two rejected applications (Cases 3 and 4) by the Spatial Planning Institute. The analysis demonstrated that the linear additive AKI (AKI_LIN) most closely reproduced these administrative decisions, while alternative aggregation and weighting schemes highlighted marginal cases where different sustainability dimensions could alter the final outcome. Independent expert revalidation confirmed that the AKI framework not only aligns with established procedures but also enhances transparency by explicitly showing how different weighting schemes affect decision outcomes. The AKI formula was applied to the four selected cases, and results were recalculated using all ten index models. This comparative approach enabled a systematic evaluation of how different weighting structures and aggregation methods influence the final classification outcomes. AKI_LIN is a baseline linear additive composite index, defined according to the stakeholder questionnaire and supported by statistical processing. AKI_GEOM applies the same weighting structure as AKI_LIN but aggregates results using the geometric mean method, providing a non-linear alternative. AKI_LIN_EW represents a linear model with equal weighting, assigning the same coefficient (0.20) to each key indicator.
- AKI_LIN_MAX emphasizes stronger differentiation among indicators by applying more pronounced weighting differences, while remaining linearly additive. AKI_INV assigns weights inversely, so that indicators rated as stronger receive proportionally lower weights, testing the sensitivity of the method to such inversion.

Finally, we have 5 models of the aggregated composite index, each prioritising a different key indicator:

- AKI_P—in this model, the spatial indicator receives a dominant weight of 0.80, while all other indicators are assigned marginal weights of 0.05. This tests whether prioritising spatial planning considerations can substantially alter the overall classification.
- AKI_R—here, the resource indicator is emphasised with a weight of 0.80, with the remaining indicators set at 0.05. The purpose is to explore how strongly resource availability alone can influence the aggregated result.
- AKI_E—this version prioritises the environmental dimension (0.80), reducing the others to 0.05. It highlights the effect of environmental protection when treated as the overriding criterion
- AKI_G—in this sensitivity model, the economic indicator dominates (0.80), with 0.05 allocated to all others. The model illustrates how economic arguments could reshape the final assessment when placed at the forefront.
- AKI_S—this version assigns 0.80 to the social-sustainability indicator, with 0.05 for each remaining domain. It provides insight into the consequences of prioritising community acceptance and social factors above all else.

The rationale for developing these five sensitivity models was to assess the robustness of the AKI framework by systematically prioritising each key indicator, thereby evaluating how individual sustainability dimensions influence the overall classification outcomes. Results from the baseline AKI_LIN model closely reproduced administrative practice, accepting Case 1, partially accepting Case 2, and rejecting Cases 3 and 4. This alignment suggests that the linear additive approach reflects decision-making patterns already established by the Spatial Planning Institute.

- AKI_GEOM penalised low-performing sub-indicators disproportionately, resulting in rejection of three out of four applications. This suggests that the model is overly restrictive and fails to account for compensatory effects often present in real evaluations.
- AKI_LIN_EW also performed poorly, as it ignores the differentiated importance of indicators. By treating all indicators treated as equally significant, the index undervalued stronger dimensions and produced excessively conservative outcomes.
- AKI_LIN_MAX amplified differences between indicators, produced inflated values. As a result, even the weakest cases were partially accepted, undermining the discriminatory capacity of the index.
- AKI_INV assigned lower weights to stronger sub-indicators, generating inconsistent results and confirming that such artificial weighting schemes are not methodologically defensible.
- Sensitivity tests prioritising spatial (AKI_P) and economic (AKI_G) indicators yielded intermediate outcomes, Cases 1 and 2 were partially accepted, but weaker applications were consistently rejected. These results confirm that neither dimension alone can drive a robust decision without balancing other sustainability aspects.
- When resource availability was prioritised (AKI_R), only Case 1 was accepted. This reflects the high weight respondents assigned to resource-related indicators, but also demonstrates that such dominance can exclude other relevant considerations.
- AKI_E generated the most permissive results, with Case 1 fully accepted and all others at least partially validated. This shows that strong emphasis on environmental sub-indicators can overshadow weaknesses in spatial, economic, or social criteria.
- AKI_S also displayed leniency, allowing partial acceptance of three cases. This outcome highlights the decisive role of social acceptability and stakeholder perception in borderline applications.

Table 7 presents the sub-indicator scores for each case and the resulting AKI values under the ten tested models. This comparative overview highlights how different weighting schemes and aggregation methods shape the final decision [40].

The table summarises the performance of all ten AKI models across the four selected applications. The results indicate that AKI_LIN most closely reproduces the original administrative outcomes, whereas alternative models emphasise different sustainability dimensions, resulting in shifts in classification. For example, AKI_E consistently produced higher values, even in borderline cases, demonstrating the strong influence of environmental criteria when prioritized. In contrast, AKI_GEOM and AKI_INV yielded implausible results, which confirms their limited applicability in practice. For reasons of transparency and reproducibility, the complete dataset of sub-indicator values (PP1–SP5) used in the aggregation process is included in Appendix B. This allows all intermediate calculations and weighting effects to be verified and provides a full basis for further methodological analysis.

Table 7. Performance of the ten AKI models across four applications [40].

Model	Request 1	Request 2	Request 3	Request 4	Interpretation
AKI_LIN	71.7	41.3	29.7	26.1	Closest to expert decisions
AKI_GEOM	66.6	0.0	0.0	17.1	Overly restrictive
AKI_LIN_EW	60.0	34.4	23.2	20.0	Undervalues strong indicators
AKI_LIN_MAX	77.6	46.9	33.3	33.0	Inflated, weak discrimination
AKI_INV	48.1	29.4	17.3	14.7	Inconsistent, methodologically weak
AKI_P	51.0	31.0	25.8	12.7	Spatial dominance, limited balance
AKI_R	81.0	27.0	21.6	12.7	Resource dominance, restrictive
AKI_E	80.2	57.6	36.3	52.8	Permissive, environment dominant
AKI_G	51.0	33.4	22.2	12.7	Economic dominance, partial balance
AKI_S	66.0	42.8	34.4	12.7	Social acceptance lenient

Note: For clarity of presentation, numerical values have been rounded to one decimal place; full precision values are available in the underlying dataset (Appendix B).

Discussion of Results and Their Interpretation

- Based on the sensitivity analysis, several key insights clarify the strengths and weaknesses of the tested AKI models.
- The proposed aggregate composite index AKI_LIN was the only variant that successfully classified all four cases into three distinct categories, fully aligning with the expert decisions previously issued for exploitation requests.
- AKI_GEOM, a type of aggregate composite index, assumes a value of 0 if at least one sub-indicator is rated 0 and does not allow compensation for that indicator with a higher value of another sub-indicator. Therefore, this form of aggregate composite index is entirely unacceptable.
- AKI_LIN_EW, a type of aggregate composite index that assigns equal weight to all sub-indicators, generated substantially lower index values and failed to capture the relative significance of stronger factors. This result highlights the necessity of applying differentiated weighting rather than treating all dimensions as equally important.
- AKI_LIN_MAX recognises the importance of individual key indicators and sub- indicators in the overall calculation of the aggregate composite index by assigning higher weights to those that are more prominent (in terms of higher mode, arithmetic mean, and greater negative skewness in the survey). However, in this case, the final values for AKI are much higher, and there are no rejected requests (even in the case of request 4, which received a very low rating from experts, only the scores for the ecological indicator are higher). This leads to the conclusion that the weights should not be stretched excessively. This indicates that while differentiation is necessary, excessive distortions in weighting undermine the index's discriminatory capacity and reduce its usefulness in decision-making contexts.
- AKI_INV is an entirely "artificially defined" aggregate composite index. It assigns a reverse meaning to sub-indicators by giving lower weights to more important ones and higher weights to less important ones. As with AKI_GEOM, the results do not reflect the real situation, and it is concluded that such weighting does not make sense, which, to some extent, emphasises the importance of other weighting methods. In this sense, AKI_INV is a purely hypothetical construct, useful only for illustrating methodological limits, rather than for practical application in sustainability assessments.
- AKI_P, AKI_G, and AKI_S favour key indicators that are the least "important" (based on the survey results). Their scores are much lower, and the conclusion is that none

of the requests could be accepted 100%. These models, by overemphasising dimensions that stakeholders considered less critical, consistently undervalued stronger sustainability drivers, resulting in uniformly weak and unbalanced outcomes.

By contrast, AKI_R and AKI_E prioritised the key indicators that stakeholders ranked as most important. As a result, both models produced outcomes in which none of the requests were rejected, underscoring the dominant influence of these dimensions in overall sustainability assessments. However, such prioritisation also raises concerns that other relevant dimensions may be overshadowed, potentially reducing the balance of the evaluation framework.

6. Conclusions and Implications of the Potential Application of AK_I in Mineral Resource Management

The presented results, including the development of I_{PREGS} indicators and the AK_I model, confirm the feasibility and justification of applying a scientifically based methodology to evaluate sustainable mineral resource management. This research provides a solid methodological foundation for strategic planning by introducing systematic procedures for selecting, quantifying, and integrating I_{PREGS} indicators, together with the AKI model, which serves as a practical tool for monitoring and improving mineral resource management in line with circular economy objectives and green GDP targets.

A comprehensive conceptual approach, coupled with commitment at the strategic level, is essential to ensure the effective and practical implementation of the proposed framework. The combination of qualitative and quantitative research confirmed a critical strategic determinant: a necessary element for rational and sustainable mineral resource management that can improve current practices, reduce systemic inefficiencies, and strengthen theoretical perspectives. Accordingly, effective collaboration among state and local authorities, public institutions, environmental agencies, concessionaires, and civil society organisations therefore remains essential in all procedures concerning exploration and exploitation permits. Mineral resources must therefore be managed in accordance with the principle of sustainable development, with I_{PREGS} indicators and the AK_I model serving as practical instruments for decision-making in the rational use of limited and non-renewable resources. Where different AK_I variants produce conflicting results, policymakers should use the linear additive model (AKI_LIN) as the primary benchmark, while interpreting sensitivity models (such as AKI_R and AKI_E) as complementary perspectives that highlight trade-offs between sustainability dimensions. For applicants whose requests are only partially approved, the AKI framework identifies which sustainability dimensions require improvement, offering clear guidance on revising documentation, introducing mitigation measures, or adapting projects before resubmission. Future research should update and revise I_{PREGS} indicator datasets every three years to ensure that the AKI framework captures changing geological, spatial, economic, environmental, and social conditions, thereby aligning with policy objectives and development strategies. Beyond methodological development, the AK_I framework is intended for operational use: it can guide administrative bodies in permit evaluation, help concessionaires align projects with sustainability benchmarks, and provide communities with transparent insight into how competing interests are balanced in final decisions. Further research should extend the sample to other mineral resources, additional locations within Varaždin County and other parts of Croatia and broaden the set of validated indicators applied in sustainable mineral resource management. It should be acknowledged that a decision-making is not a uniform or fixed process but one that depends on specific contextual conditions. Overall, the proposed methodology for selecting, quantifying, and integrating indicators, combined with the AK_I model, provides both relevant scientific insights and a practical foundation for decision-making in sustainable mineral resource management.

Author Contributions: Conceptualization and creation of the idea for the paper, writing of the discussion and conclusion section, and methodology, M.S. and D.P.; software, I.Z.; preparation of the comprehensive literature overview, introduction section, and table validation, K.N.M.; writing of the introduction and methodology sections, review and editing of the whole paper, D.P.; methodology, formal analysis, software, validation, discussion of the results, and writing—review and editing, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data presented in this study are available on request from the corresponding author.

Conflicts of Interest: Darko Pavlović is an employee of Plinacro d.o.o., and Ivan Zelenika is an employee of Podzemno skladište plina d.o.o. The paper reflects the views of the scientists, not the companies.

Appendix A. Full Statistical Measures for Selected Sub-Indicators

Table A1. Full Statistical Measures for Selected Sub-Indicators.

Sub Indicator	Mean (A.M.)	Mode (M)	Median (m)	Standard Deviation (σ)	Variance (Var)	Coefficient of Variation	Coefficient of Skewness
PP1	3.68	5	4	1.359205682	1.833855969	0.368966014	−0.6470946
PP2	2.71	3	3	1.240717166	1.528060121	0.457283291	0.13772979
PP3	3.57	4	4	1.347878184	1.803416955	0.377184019	−0.7112021
PP4	3.50	5	4	1.424650704	2.014705882	0.407043058	−0.5616023
PP5	3.80	5	4	1.428907135	2.026762543	0,375882728	−0.9579887
RP1	3.59	5	4	1.378865991	1.887187929	0.384601051	−0.4834479
RP2	4.03	5	4	1.119306427	1.243566529	0.277769058	−1.1609671
RP3	3.32	3	3	1.274840329	1.613267734	0.384430787	−0.3752287
RP4	4.01	5	5	1.218613699	1.474019204	0.304090295	−0.9686882
RP5	4.20	5	5	1.178950273	1.37970372	0.280800766	−1.3847205
EP1	4.27	5	5	0.930686021	0.859807526	0.217854215	−1.0181759
EP2	4.21	5	4	0.922220254	0.844236592	0.218886483	−0.9562779
EP3	3.63	5	4	1.297188353	1.670233196	0.357388628	−0.6128785
EP4	3.90	5	4	1.138695733	1.28702332	0.29169625	−0.732039
EP5	3.57	4	4	1.18448117	1.392679498	0.332143174	−0.5672635
GP1	3.13	3	3	1.237211543	1.519269325	0.394729397	−0.2594175
GP2	3.09	3	3	1.153371563	1.320338605	0.373313501	−0.2369396
GP3	3.49	4	4	1.248969949	1.548284696	0.358376816	−0.5414548
GP4	3.56	5	4	1.330843446	1.758024691	0.374299719	−0.5068019
GP5	3.68	5	4	1.354577286	1.82087291	0.368152748	−0.7927985
SP1	3.35	4	4	1.28763619	1.645633771	0.384283406	−0.6393035
SP2	4.16	5	5	1.11212226	1.227654321	0.267623004	−1.4034760
SP3	3.44	4	4	1.154726359	1.323136095	0.335826458	−0.6453799
SP4	3.54	5	4	1.379853276	1.889786144	0.389263871	−0.6523059
SP5	353	5	4	1.334557424	0.389263871	0.377651356	−0.6269337

Appendix B. Sub-Indicator Assessments for Each Case (Requests 1–4) and Resulting AKI Model Values

Table A2. Sub-Indicator Assessments for Each Case (Requests 1–4) and Resulting AKI Model Values.

Sub-Indicators	Request 1	Request 2	Request 3	Request 4
PP1	60	60	0	10
PP2	20	35	20	10
PP3	40	50	25	10
PP4	20	0	0	10
PP5	60	0	60	10
RP1	60	15	20	10
RP2	100	60	50	10

Table A2. *Cont.*

Sub-Indicators	Request 1	Request 2	Request 3	Request 4
RP3	60	0	0	10
RP4	80	30	20	10
RP5	100	0	0	10
EP1	100	100	60	80
EP2	100	90	60	80
EP3	80	0	0	50
EP4	60	40	20	30
EP5	60	35	20	60
GP1	20	45	15	10
GP2	20	0	0	10
GP3	40	50	30	10
GP4	60	0	0	10
GP5	60	50	40	10
SP1	80	50	60	10
SP2	40	0	0	10
SP3	80	65	50	10
SP4	40	40	0	10
SP5	60	45	30	10
AKI_LIN	71.7	41.3125	29.65	26.05
AKI_GEOM	66.59532	0	0	17.07793
AKI_LIN_EW	60	34.4	23.2	20
AKI_LIN_MAX	77.6	46.9	33.3	33
AKI_INV	48.1	29.4125	17.25	14.65
AKI_P	50.95	30.9625	25.7625	12.675
AKI_R	80.95	27.025	21.6375	12.675
AKI_E	80.2	57.5875	36.2625	52.8
AKI_G	50.95	33.4	22.2	12.675
AKI_S	65.95	42.775	34.3875	12.675

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