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Optimizing Selection of Sustainable Material-extraction Sites with GIS-based Decision-support Systems (AHP/MACBETH): In-depth Case Study from Settat, Morocco

Abstract: In today's world, sustainability is crucial, particularly in managing natural resources for sustainable development. Often, environmental impacts of new activities are overlooked, worsening the effects on already vulnerable environments. Our study uses two multi-criteria decision-making tools, MACBETH and AHP, integrated with GIS technology, to evaluate quarry sites in Settat Province, Morocco. This methodology classifies sites by suitability, based on criteria aligned with sustainable development goals.

We found a high consistency between MACBETH and AHP, with less than 4% divergence in criteria weighting, confirming the robustness of our integrated approach in making location-based decisions for quarries. The resulting maps clearly delineate zones from unsuitable to highly suitable for quarrying.

Beyond assessing current quarrying practices, our findings offer strategic insights for future site planning and establishment, showcasing adaptability and potential for replication. This research provides a practical model for improving material extraction practices, aligning with sustainable development needs, and serving as a valuable tool for policymakers and industry stakeholders.

Keywords: sustainable development, MACBETH, AHP, GIS, material extraction

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1. Introduction

The material-extraction sector is pivotal in driving the socio-economic development of nations, serving as a foundational supplier of the raw materials that are essential for infrastructure, construction, public works, and real estate development. Beyond supplying critical materials, this sector substantially bolsters local economies by generating revenue through extraction taxes and fees, creating employment opportunities, and enhancing regional economic prosperity. However, the environmental footprint of its operations is significant, compelling a transition toward more sustainable and eco-friendly practices. In this context, [1] underscored the importance of sustainable development goals (SDGs) within this sector. Specifically, stakeholders in Poland, Greece, and Slovakia prioritize SDG 9 (industry, innovation, and infrastructure), SDG 8 (decent work and economic growth), and SDG 7 (affordable and clean energy) as being integral to their operational success and long-term sustainability.

Within the heart of Morocco lies Settat Province, a region that is steeped in a rich tapestry of history and culture and an ever-evolving narrative of human endeavor. Tracing its roots back to the Almohad dynasty, Settat has grown from its historical foundations to become an economic nexus, propelled in part by its material-extraction sector. The province's strategic position (just a stone's throw from Casablanca – Morocco's economic juggernaut) endows it with a unique advantage in the raw materials market. Yet, this advantage brings with it the pressing need to reconcile economic growth with the stewardship of Settat's diverse and picturesque landscapes – from its fertile agricultural heartlands to the undulating contours of its outskirts (all resonant with the echoes of its ancient past).

In response to these challenges, our study introduces a novel decision-making methodology that integrates a decision-support tool with geographic information system (GIS) technology, aiming to holistically classify extraction sites based on their sustainability potentials by incorporating economic, social, and environmental factors. Central to our methodology are MACBETH (measuring attractiveness by a categorical-based evaluation technique) and AHP (analytic hierarchy process) – these were used to evaluate site options with a focus on environmental impacts, economic viability, and social implications. As [2] suggested, this comprehensive assessment involves measuring the attractiveness of each option, weighting criteria, and aggregating elements to effectively rank the sites and criteria. As was discussed by [3, 4], the integration of GIS technology enables spatial visualizations of suitable, unsuitable, and particularly favorable extraction sites, with our case study featuring 61 quarries in Settat, Morocco. We treat 'sustainability' as a multi-dimensional framework that guides our selection process in order to ensure balanced outcomes.

Our research was driven by two critical questions: how do these GIS-based decision support systems influence the selection of environmentally sustainable quarry sites, and what role do they play in enhancing economic and social sustainability within the quarrying industry?

We hypothesized the following:

(H1) The integration of MACBETH and AHP within GIS-based systems significantly improves environmental sustainability by accurately assessing ecological impacts.

(H2) These systems enhance economic and social outcomes by prioritizing sites that foster local economic development and community welfare.

This methodology aims to align quarry-site selection with sustainable development goals, establishing a model for future evaluations.

Our research addresses critical questions about the contribution of the material-extraction sector to sustainable development within a territory, the key criteria that influence quarry-location selection, and assesses and plans for future sustainable installations. As [5] noted, SDGs 9 and 7 are crucial for the raw materials sector, with digital transformation, recycling, and resource efficiency posing key challenges. Furthermore, [6] emphasized responsible materials management for a resource-efficient and low-carbon society.

The goal of our study was to align the three pillars of sustainable development (economic, social, and environmental) with the growth objectives of the material-extraction sector. We contend that sustainable practices can be economically beneficial and environmentally friendly.

To contextualize our research, we conducted a comprehensive bibliographic review on multi-criteria decision-making methodologies. This review included seminal contributions by [7] on the MACBETH method, by [8] on multi-criteria decision analysis (MCDA), and by [9] on MACBETH's practical implementation. Focusing on sustainability, [10] applied multi-criteria methodologies to assess environmental impacts in the quarry sector, while [11] highlighted sustainable practices in natural resource management. In addition, [12, 13] applied these methodologies to evaluate quarry locations, considering sustainable development aspects, and [14] emphasized the integration of ecosystem services into municipal environmental policies. Additionally, [15] discussed the role of GIS and technology in enhancing sustainable practices within the framework of Smart Industry 4.0 and 5.0. Studies by [16–19] demonstrated how GIS could improve spatial data representation for more efficient planning in land management and resource allocation when combined with decision-making methodologies like AHP.

Other decision models like ELECTRE and PROMETHEE have distinct applications that are suited to specific decision-making contexts. ELECTRE is particularly useful in environmental settings where the criteria are non-compensatory – ideal for situations where trade-offs are not permissible (as was highlighted in the studies by [20, 21]). PROMETHEE is valued for its flexibility in outranking alternatives and is commonly used in energy policy development due to its adeptness at handling both quantitative and qualitative data (as was noted by [22]).

However, we chose AHP and MACBETH for our specific project needs. AHP excels at structuring complex decision problems into clear hierarchies, facilitating a detailed analysis of multi-faceted economic, environmental, and social factors. MACBETH is particularly beneficial in scenarios where decision criteria are qualitative and difficult to quantify, efficiently transforming subjective assessments into measurable scales. This feature was crucial for our study; it often deals with data that is not easily quantifiable yet requires a rigorous structured decision-making process. The combined strengths of AHP and MACBETH provided a comprehensive and balanced approach to assessment, significantly enhancing our capability for making informed and effective decisions.

Our approach adopted a holistic perspective to address the complex interactions between resource extraction and sustainable development, driven by ecological limits and the necessity for sustainable management practices.

Our resources are inevitably being depleted under current consumption patterns [23, 24]. In response to this, the ecological footprint was introduced to accurately quantify environmental demands [24]. Building on this concept, a sustainable framework was proposed that effectively aligned human needs with planetary boundaries [25].

Building on these insights, recent empirical studies such as those by [26] have underscored the importance of effective environmental governance, finding that robust governance significantly reduces resource footprints when coupled with high-quality institutional frameworks and technological innovations – especially in scenarios of high resource consumption. This indicated a critical need for overarching governance frameworks that effectively manage the environmental impacts of material extraction [27]. Additionally, [28] highlighted the crucial role of governance structures in protecting local communities from the adverse effects of extraction activities (such as environmental degradation and social conflicts), supporting the necessity for a more inclusive and effective governance approach that integrates local communities into the decision-making processes, thus ensuring their benefit and protection. Furthermore, [29] discussed the dual impact of ferrous metal production on urban development, noting that, while it initially stimulated economic growth, it posed significant long-term environmental risks. The authors advocated for integrated governance approaches that included rigorous environmental policies, renewable energy investments, and forest conservation; these were deemed to be essential for mitigating the adverse impacts of extraction activities and ensuring sustainable urban development.

By bridging the gaps in the literature and integrating these foundational theories with contemporary empirical studies, our research offers a comprehensive view of the challenges and solutions that are at the intersection of material extraction and sustainable development. This holistic approach is crucial for advancing our understanding of how material-extraction practices can align with global sustainability goals, thus positively contributing to economic growth, environmental conservation, and social equity. This study addresses critical questions regarding the contribution of the material-extraction sector to sustainable development within a territory, focusing on the key criteria that influence quarry-location selection and assessing and planning for future sustainable installations [6, 12, 13]. By synergizing multi-criteria methods with GIS technology, our research aims to optimize development project evaluation and planning, thereby significantly contributing to the goals of sustainable development. The remainder of this paper is structured as follows: Section 2 reviews the related literature in more detail, Section 3 describes the tools and methods that were used, Section 4 presents and discusses the results, and Section 5 concludes with a summary of our findings and implications for future research.

2. Materials and Methods

2.1. Context and Problem

For many years, the selections of material-extraction sites were primarily focused on economic profitability (such as the availability and abundance of deposits and their proximity to consumption areas) and social factors (like job creation). However, the environmental impact of these activities was often overlooked or minimally considered. The growing negative effects of the extractive industry (increasingly being felt by local communities) coupled with a heightened global consciousness about environmental preservation have compelled decision-makers to reassess their strategies.

Recognizing this need, a more balanced approach that aligns with the principles of sustainable development has become essential. By considering the economic, social, and environmental dimensions equally, a more harmonious coexistence between extraction activities and the surrounding environment can be achieved. This shift not only aims to mitigate any adverse impacts but also to enhance the positive outcomes of these activities.

In line with this approach, we have explored the application of two decision-making methodologies in the quarrying sector of Settat Province. This initiative was designed to assess the current state of material extraction and explore opportunities for optimizing future activities. By integrating these comprehensive decision-making tools, our goal was to ensure that material extraction contributes positively to sustainable development, balancing economic needs with environmental and social responsibility.

2.2. Study Area Presentation

The study area was the territory of Settat Province in Morocco, which is located in the center of the country on an area of approximately 7.220 km². Being at the heart of the Chaouia plain, it contains a very significant deposit potential and, at the same time, is characterized by its proximity to Casablanca, which is the most important consumption area for raw materials in Morocco. These assets make it one of the most attractive territories in Morocco for the material-extractive industry. Therefore, Settat Province presented a very suitable framework for studying the application of this study, as the focus could be on three-dimensional development (economic, social, and environmental) in order to evaluate the existing situation and predict the opportunity to optimize future locations (Fig. 2).

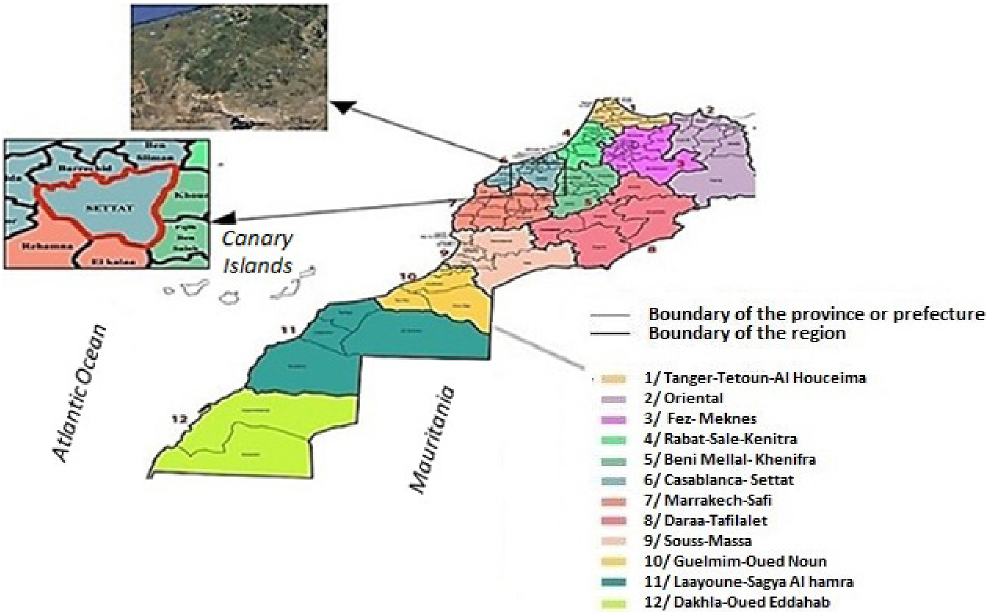

Fig. 1. Overview of study area

2.3. Decision-making Model Structure

The two proposed decision-making tools were based on the fundamental sustainability criteria and were chosen with reference to the principles of sustainable development, expressing the preferences that were previously agreed upon by decision-makers to be applied to quarries (whose choices reflected the geographical distribution at the study area level as well as the typology of the materials).

Our decision-making framework was rigorously developed to reflect a balanced integration of environmental, economic, and social considerations. This was achieved by applying advanced analytical techniques that were continually refined through feedback from field experts. With their deep understanding of the regional context and its unique environmental challenges, these experts provided critical assessments that guided the weighting of our criteria and the interpretation of the data.

The exhaustive analysis and collection of information related to quarrying concerned 61 existing quarries in Settat Province. This exploration consisted of collecting reliable and relevant data through field visits and studies (especially environmental impact studies). The collected data consisted of qualitative and quantitative variables as well as vectorial and non-vectorial variables. This combination of data allowed us to feed each of our models in order to reconstruct reality as comprehensively as possible. This allowed us to obtain very important information on their management and draw up an inventory of current exploitation (positive or negative impacts).

Spatial Assumptions and Metric Specifications

In conducting our multi-criteria GIS analysis, several spatial assumptions and metric specifications were defined in order to ensure the accuracy and relevance of our findings. The primary spatial data that was utilized encompassed high-resolution satellite imagery and topographic maps of Settat Province (with a resolution of 1 meter per pixel). This granularity allowed for the precise delineation of the quarry-site boundaries and the accurate assessment of the surrounding environmental features.

SPATIAL ASSUMPTIONS

Continuity of terrain. We assumed that the terrain within our study area was continuous and that topographic changes were gradual unless interrupted by significant natural or anthropogenic barriers. This assumption was critical for modeling the erosion potential and water-runoff patterns around the proposed quarry sites.

Uniformity of land use. The land-use data was assumed to be uniform within each classified zone based on the most recent satellite imagery. However, seasonal variations and recent developments without updated records posed limitations to this assumption.

Stability of environmental features. Environmental features such as water bodies, forests, and wildlife corridors were assumed to be stable within the timescale of our analysis. Any long-term environmental changes due to climate or human activities were not dynamically modeled but rather noted as potential areas for future research.

METRIC SPECIFICATIONS

Buffer zones. Buffer zones of 500 m were established around each potential quarry site to assess their impacts on adjacent residential areas and ecological sensitive zones. These zones were derived based on environmental impact studies that were specific to the region.

Distance metrics. Euclidean distances were used to calculate each site's proximity to such infrastructure as roads and utilities, which are crucial for operational logistics. This metric helped us evaluate the economic viability concerning transportation costs.

Elevation and slope. The elevation data from digital-elevation models (DEMs) were used (with a contour interval of 2 m). Slope calculations were performed to identify those areas with slopes greater than 45 degrees (which were automatically excluded from further analysis due to their high erosion risks).

These spatial assumptions and metrics underpinned our GIS analysis and provided a structured framework for evaluating each criterion. This foundation enhanced the adaptability of our methodology to various regions and different environmental and regulatory contexts.

Criteria Selection

The selected families of criteria were the three pillars of sustainable development (economic, social, and environmental dimensions); these were subdivided into several criteria as follows (Fig. 2).

Indeed, the 16 criteria were chosen to ensure the holistic evaluation of quarry sites in Settat Province, reflecting both local and broader sustainability goals.

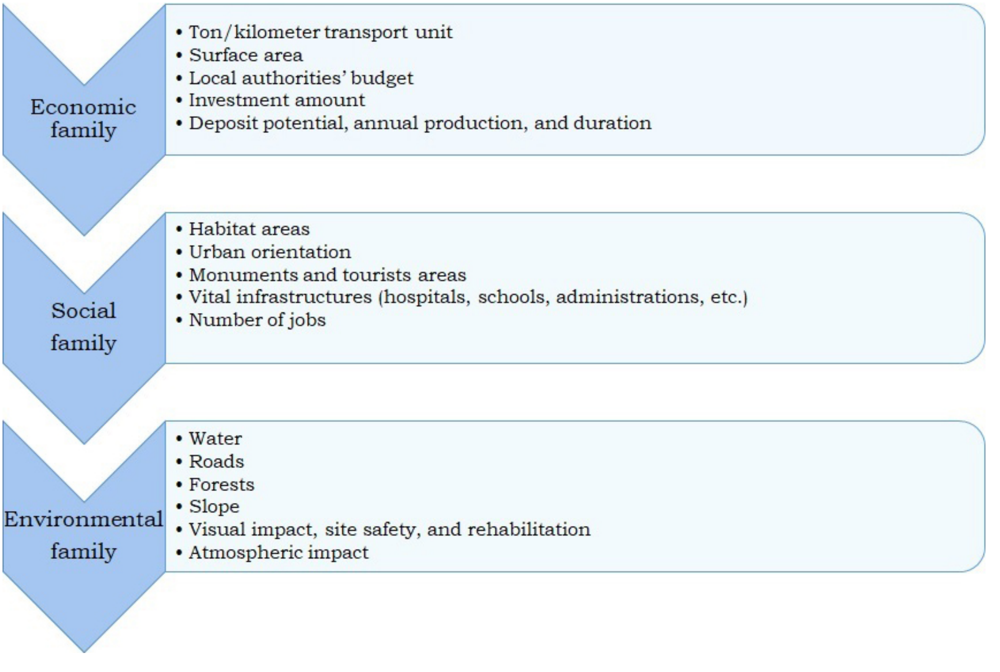

Fig. 2. Criteria by families

ECONOMIC CRITERIA

Ton/kilometer transport unit. Reflects the economic efficiency of transporting materials. Lower transportation costs contribute to lower overall costs of materials, which is crucial for the economic sustainability of construction and infrastructure projects (thus, acting like a stimulant).

Surface area. Larger areas are preferred, as they allow for economies of scale, making the operations more economically viable over the long term and serving as stimulants by enhancing profitability.

Local authorities' budget (CT). Incorporating the financial benefits to local governments ensures that quarry operations contribute positively to local economic development (thus, classified as a stimulant).

Investment amount (MI). Higher investments in quarry operations are indicative of robust economic activity and a commitment to long-term regional economic contributions (marking this as a stimulant).

Deposit potential, annual production, and duration. These factors are critical for ensuring that a quarry can meet the demand for materials over a sustained period, enhancing the economic stability of the region (and acting like a stimulant for selection).

SOCIAL CRITERIA

Residential areas, urban orientation, monuments, places of worship, tourist areas (CR S8), vital infrastructures (hospitals, schools, administration, etc.). Protecting these areas from the negative impacts of quarrying ensures that the social fabric and heritage of a community are maintained (making this a stimulant).

Number of jobs. Job creation is a significant social benefit that provides local employment opportunities and enhances community welfare (thus, this is a stimulant).

ENVIRONMENTAL CRITERIA

Water. Preserving water quality and availability is critical – especially in arid regions like Settat. Scarcity and vulnerability to pollution make this a destimulant.

Roads. Minimizing the impact on local infrastructure reduces environmental degradation and nuisance (classified as destimulants to discouraging sites that could cause significant infrastructural damage).

Forests. Forests are vital for biodiversity and ecological balance; their degradation is a significant environmental threat (making their protection a destimulant to quarrying in such areas).

Slope. Steeper slopes are excluded from quarrying activities due to their susceptibility to erosion and other ecological disturbances (this criterion is a destimulant, as it helps prevent landscape destabilization).

Visual impact, site safety, and rehabilitation. Ensuring that quarries do not permanently scar the landscape and are rehabilitated post-use are crucial for long-term environmental stewardship (making this a destimulant to prevent negative visual impacts).

Atmospheric impact. To protect the environment from nuisances, a classification system that is based on the protection measures has been established to manage the dust and emissions from quarry sites. This approach ensures that operations align with environmental health standards, effectively mitigating atmospheric nuisances (making this a destimulant).

Analysis of Criteria Dependencies

In developing our decision-making framework, understanding the interdependencies among the selected criteria was crucial. These relationships could have significantly influenced the outcomes of our site evaluations – affecting both the accuracy and fairness of the decision-making process.

METHODOLOGY FOR ANALYZING DEPENDENCIES

We conducted a statistical analysis using Pearson's correlation coefficients to explore the relationships between pairs of numerical criteria. This analysis was pivotal in uncovering how different criteria influenced one another (which, in turn, affected the overall assessment of the quarry sites).

IDENTIFIED CORRELATIONS

A significant positive correlation was found between the 'Deposit potential, annual production, and duration' and the 'Number of jobs' that were created. This correlation highlighted that quarry sites with greater deposit potentials not only promised longer operational life and economic benefits but also offered more employment opportunities (thus, gaining greater acceptance from local communities).

A negative correlation was detected between 'Ton/kilometer transport unit' and 'Atmospheric impact.' This finding indicated that those sites that were further from raw material sources (which required more transport) potentially had higher emissions and dust levels (thus, complicating environmental management efforts).

PURPOSE AND IMPLICATIONS OF DEPENDENCY ANALYSIS

Adjusting criteria weights. In response to the identified negative correlation between 'Ton/kilometer transport unit' and 'Atmospheric impact,' we adjusted the weighting of these criteria within our decision models. Recognizing that longer transportation distances are associated with increased emissions and dust, we increased the weight that was assigned to the atmospheric impact considerations. This adjustment ensured that the environmental management challenges were appropriately accounted for in the overall evaluation of the quarry sites – particularly in assessing their sustainability and compliance with environmental standards.

Model refinement. The analysis helped refine our decision models by providing a deeper understanding of how the different criteria interacted. This ensured that our models did not overemphasize correlated factors (thus, maintaining a balanced approach to site selection).

INTEGRATION INTO DECISION MODELS

The insights that were obtained from analyzing these dependencies were crucial for enhancing the MACBETH and AHP methodologies. Adjustments were made to both the scoring systems and the weighting schemes in order to reflect the nuanced understanding of the criterion interplay. This methodological refinement was instrumental in ensuring that our evaluation of the potential quarry sites was both comprehensive and precise (thus, leading to better-informed and sustainable site-selection decisions).

Data Collection and Analysis

To thoroughly assess the sustainability of the material-extraction sites, we meticulously gathered a diverse data set from Settat Province in Morocco. This data collection occurred over a six-month period (from January through June 2023) and encompassed both field measurements and secondary data sources.

DATA SOURCES

The primary data was collected through extensive field visits, which involved direct observations, GPS measurements, and interviews with local stakeholders. The secondary data was sourced from existing environmental impact reports and local government databases, which provided historical data on quarry operations and their impacts.

DATA-COLLECTION PERIOD

The data was gathered systematically during the first half of 2023 in order to ensure that the most recent and relevant information was used in our analysis.

DATA DESCRIPTION

Our data set included both qualitative and quantitative elements. Qualitative data included descriptions of local community feedback and expert opinions on environmental impacts. Quantitative data comprised of measurements such as the area of the land that was affected, pollutant levels, and economic data such as job-creation numbers and local revenue impacts.

Statistically, the quantitative data showed the following:

- mean area of quarries: 15.2 ha (with standard deviation of 5.3 ha);
- average annual production: 10,000 metric tons (with variability depending on material type and quarry size);
- employment: each quarry supports average of 50 local jobs, with standard deviation of 10 jobs (thus, reflecting economic importance of these sites).

This detailed data collection and characterization were crucial for understanding the multi-dimensional impacts of quarry operations and formed the basis for our sustainability assessments when using the AHP and MACBETH decision-making tools.

Structuring Decision Models

In addressing our decision problem, we focused on selecting the most suitable methods, ultimately narrowing our choices down to MACBETH (measuring attractiveness by a categorical-based evaluation technique) and AHP (analytic hierarchy process). These methods were particularly apt for our multi-criteria decision-making scenario, as they were characterized by a limited number of decision-makers that possessed various conflicting viewpoints. Both MACBETH and AHP excel in situations that require complete aggregation; they effectively produce hierarchical structures and comprehensive scales that illustrate the rankings of alternatives and criteria based on a clearly defined notation system. This structured approach ensures a thorough and nuanced evaluation of the decision-making process.

MACBETH APPROACH

The deployment of the MACBETH decision-making tool represented a sophisticated approach for evaluating multiple alternatives against a spectrum of criteria. This technique distinguishes itself by quantifying the relative attractiveness between options, thereby assigning scores that reflect their performance against each criterion. A unique feature of MACBETH is its use of qualitative judgments to articulate the weights of criteria, which are then converted into a quantitative scale.

As evaluators input their qualitative assessments into the M-MACBETH software, the tool's advanced algorithm actively checks for consistency within these judgments. This tool is designed to identify any discrepancies and offers recommendations to address them, ensuring that the decision-making process is both rigorous and coherent. Following this, MACBETH generates a scoring scale for each criterion, allowing for a comprehensive assessment of each option's overall appeal.

The resultant overall score for an option is the aggregation of its weighted scores across all criteria, thus providing a holistic picture of its attractiveness. This scoring is integral for formulating a ranked list of options, reflecting a cumulative evaluation of their performance against the predefined criteria set [7].

This methodological process is encapsulated in a sequence of steps (as illustrated in Figure 3).

In this approach, a number that qualifies its attractiveness (in the decision-maker's view) on a criterion is aggregated to each option. In this work, we opted for indirect comparison with pre-defined qualitative or quantitative performance levels for each considered criterion (Table 1). The performance of each option is obtained through the value system, which allows for its conversion into a numerical scale.

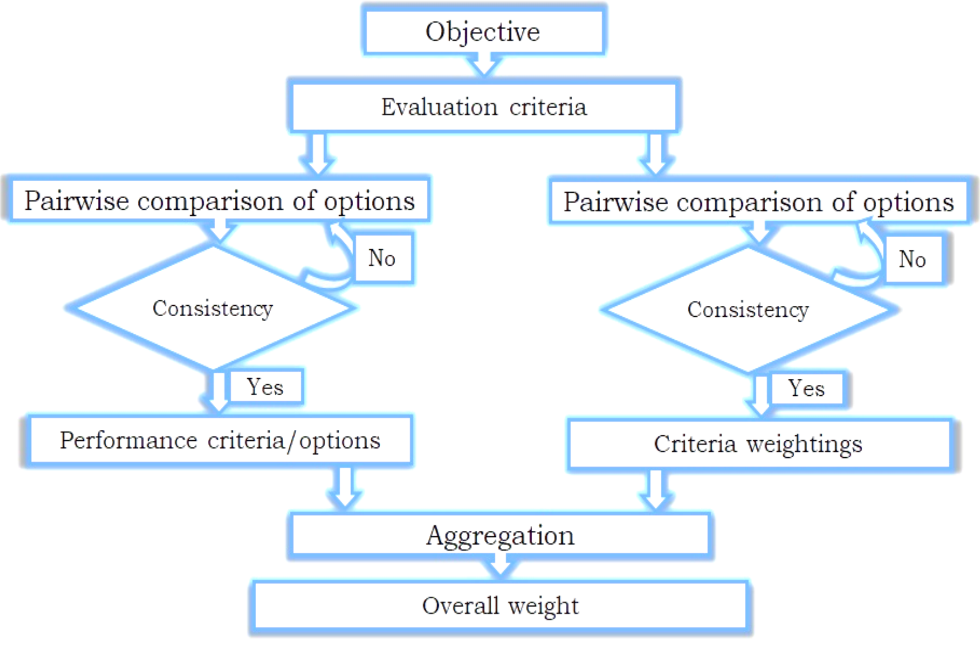

Fig. 3. Description of methodology and steps that were followed

Table 1. Indirect comparison of performance levels

	Criterion family					
	Economical qualitative	Social qualitative	Environmental qualitative	Economical quantitative	Social quantitative	Environmental quantitative
Criterion	Ton/kilometer transport unit	Urban planning	Roads	Local authorities' budget	Habitat areas	Water
	Surface area	Monuments, tourist areas, and places of worship	Visual impact, site safety, and rehabilitation	Investment amount	Vital infra-structures (hospitals, mosques schools, etc.)	Forests
	–	–	Atmospheric impact	Deposit potential, annual production, and duration	Number of jobs	Slope

ANALYTICAL HIERARCHY PROCESS APPROACH

The analytical hierarchy process (AHP) method is one of the multi-criteria decision-making (MCDM) methods that were created in the 1970s by Professor Thomas L. Saaty [30]. Like any multi-criteria analysis, AHP includes four major essential steps (Fig. 4).

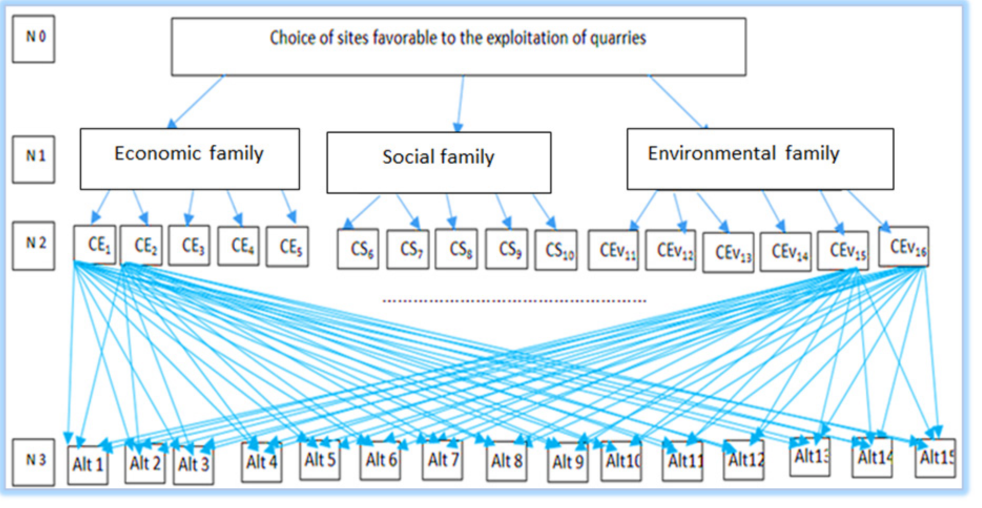

Fig. 4. AHP hierarchical tree

Firstly, we defined the possible solutions (actions or scenarios) and designated the problem (sorting, choice, etc.); then, we identified the criteria and alternatives. After this, we evaluated each action against the criteria through the calculation of a synthetic score (a value that ranged from 1 through 9), which was then aggregated and calculated based on the ranking and weighting of all of the criteria that were taken into account in the decision. Next, we modeled the global preferences and performance-aggregation procedures (the criteria to be retained, the relative ordering of the criteria, and the alternatives) and ultimately performed a multi-criteria synthesis, which consisted of analyzing the results as well as their sensitivity and robustness.

To proceed with the pairwise comparison judgments, AHP used basic absolute value scales from 1 through 9 as well as their reciprocals.

Combination of decision-support tool and GIS. The combination of a decision-support tool and a GIS can be a decision-making tool that produces a spatial representation that visualizes a multi-criteria analysis and allows for the optimization and evaluation of development projects in order to improve the prospects and achieve sustainable development.

This combination is comprised of the following steps:
- the inventory of the elements of the tool identified a categorization of this data into two categories of criteria: exclusion criteria, and evaluation criteria;
- the establishment of exclusion criteria and evaluation criteria was done either according to legal restrictions or according to the concerns that were presented by the decision-makers.

Establishment of exclusion criteria. First, we compiled a list of the exclusion criteria as well as their conditions. An exclusion criterion designates that an area is an unsuitable area for a possible quarry site or that their locations at these sites could cause harmful environmental damage. These criteria were established based on legislative restrictions and the concerns that are presented by stakeholders in the sector (as shown in Table 2).

Table 2. Buffer distances for exclusion criteria

Exclusion criteria	Type	Buffer distance [m]
Urban planning orientation, habitat areas, vital infrastructures, and monuments	agglomeration development plan, hospitals, schools, mosques	600
Bodies of water	dams	1,000
Hydrographic network	wadi	350
Sources	–	1,000
Roads	motorways, national and regional roads	100
Forests	–	200
Slopes	areas with slopes greater than 45° avoided	

Establishment of evaluation criteria. In the second step, the areas that were obtained after the previous step were evaluated by the evaluation criteria according to a rating scale of 1 through 5 (where each rating indicated a distance interval). This evaluation aims to propose and identify unfavorable, less favorable, and highly favorable sites for accommodating this activity.

Evaluation. The utilization of overlay analysis facilitates a composite examination of diverse factors, employing an array of tools that converge on the identifications of optimal sites for specified activities. This process aligns with a predefined hierarchy of priorities that are quantified by numerical values that reflect a consensus among decision-makers on the relative importance of each criterion. The procedural flow of this analysis (captured in the sequential steps that are detailed in Figure 5) underscores the meticulous methodology that is undertaken to synthesize various data sets into a coherent decision-making framework.

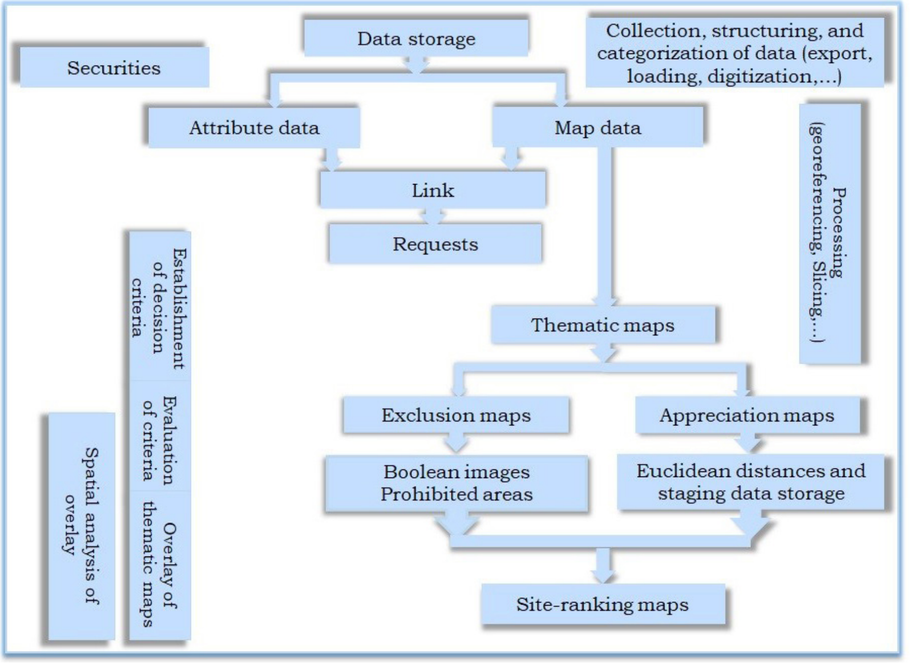

Fig. 5. Steps of followed approach

In the initial phase of our geospatial analysis, we meticulously mapped and integrated critical decision-making factors into the GIS environment (specifically, ArcGIS), converting them into a shapefile format. Following the determination of the relevant criteria for these elements, our next step was the construction of a model builder. This sophisticated sequence represented a series of interconnected operations where the output of one tool seamlessly became the input for the next, thereby facilitating an intricate web of analytical processes that support the creation and management of robust model tools.

The evaluation process unfolded through four distinct yet interrelated steps:

1. Application of exclusion criteria (buffer zone) (see Fig. 6). We applied spatial exclusion criteria to delineate the buffer zones. Utilizing the buffer tool within ArcGIS, we calculated the precise distances on a planar surface, thereby establishing safety radii around each thematic element. These exclusion zones were tailored to reflect legislative mandates and the preferences of the decision-makers, ensuring that those areas that were unsuitable for material extraction were accurately identified and preserved.
2. Application of assessment criteria (Euclidean distance) (see Fig. 7). By employing the concept of Euclidean distance, we generated thematic maps that depicted classified the distance intervals for each criterion within the study area. This classification effectively segmented the area into distinct zones according to the proximity to (or remoteness from) potential extraction sites.

3. Application of assessment criteria (reclassification) (see Fig. 8). The Euclidean distances that were previously established were then reclassified. This reclassification was informed by the decision-makers' expressed preferences, allowing us to assign appropriate weightings to different zones based on their suitabilities for quarrying.
4. Integrated thematic analysis for site selection. The synthesis of our process involved the integration of all of the thematic maps that were created in the prior steps. This integrated map visually consolidated the site rankings, providing stakeholders with a clear and actionable layout for discerning the most suitable locations for material-extraction activities.

Fig. 6. Map of network exclusion zones according to hydrography

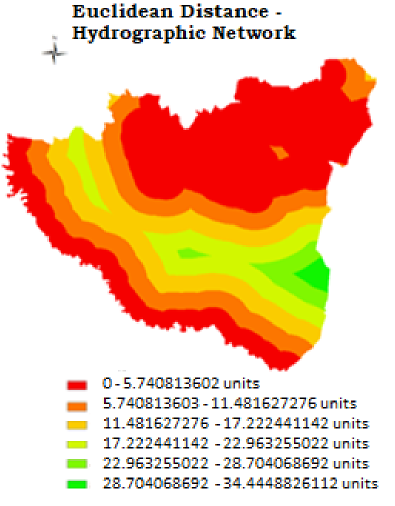

Fig. 7. Euclidean distance map according to the hydrographic network

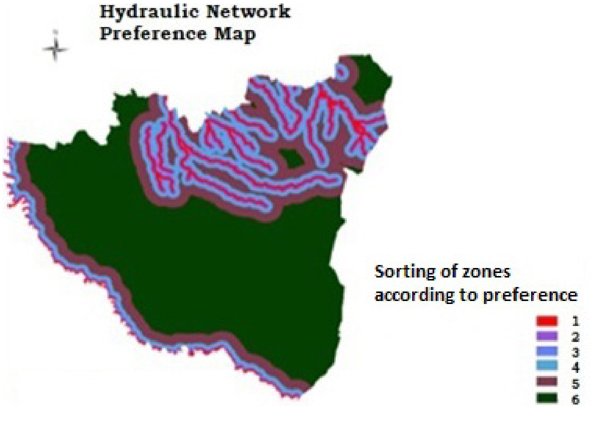

Fig. 8. Preference map according to the hydrographic network

This thorough evaluation protocol transcended basic analysis; it manifested a comprehensive approach to sustainable site selection. By encapsulating the intricacies of both the physical terrain and the socio-economic context, this ensured that the decision-making process was rooted in an equilibrium of practical considerations and strategic planning.

IT Tools Used in Study

For our analysis, we utilized the following IT tools:

- ArcGIS: employed for mapping and spatial-analysis tasks;
- M-MACBETH: used for conducting MACBETH analysis;
- Expert Choice: utilized for analytic hierarchy process (AHP) evaluations;
- R: applied for statistical analysis;
- Microsoft Excel: used for data organization and preliminary analysis;
- ERDAS Imagine: employed for satellite imagery processing.

These tools were integral for ensuring the accuracy and reliability of our data analysis and decision-making processes.

3. Results and Discussion

As evidenced by the data that is presented in Table 3, a clear alignment emerged between the sustainability objectives and the locational determinants of quarry sites within the study area when employing either the MACBETH or AHP decision-support tool. Each tool demonstrated its efficacy in correlating sustainability benchmarks with the practical indicators that were essential for quarry placement. This congruence was indicative of the robustness of both methodologies in guiding the quarry-site-selection process toward sustainable outcomes.

Table 3. Weighting of criteria by MACBETH and AHP

Criteria families	Weight [%]		Criterion	Weight [%]		
	MACBETH	AHP		MACBETH	AHP	Gap
Economic CF	38.84	38.8	Ton/kilometer transport unit	14.20	13.1	8
			Surface area	11.40	10.8	6
			Local authorities' budget	1.08	2.3	53
			Investment amount	7.96	8.2	3
			Deposit potential, annual production, and duration	4.20	4.5	7

Table 3. cont.

Social CF	28.99	8.1	Habitat areas	7.53	7.3	3
			Urban planning	4.84	4.1	18
			Historical monuments, tourist sites	0.65	1.1	41
			Vital infrastructure (hospitals, schools, mosques, etc.)	6.72	6.9	3
			Number of jobs	9.25	8.8	5
Environmental CF	32.17	33.1	Water	8.17	8.5	4
			Roads	6.99	6.9	1
			Forests	5.38	4.7	14
			Slope	0.22	1.0	78
			Visual impact, site safety, and rehabilitation	2.80	1.6	75
			Atmospheric impact	8.61	10/3	16

A further examination of the criteria weights in Table 3 revealed that economic factors such as 'Ton/kilometer transport unit' and 'Surface area' were given substantial importance in both models. This implied the prioritization of cost-efficiency and scalability in the operations, which were deemed to be essential for the long-term economic sustainabilities of the quarry sites. The close weights between the two models for these criteria indicated a shared understanding of their critical impacts on the quarrying industry.

3.1. Comparative Analysis of MACBETH and AHP Outcomes

To better understand the distinctions between the MACBETH and the AHP decision-making methodologies that were employed in this study, we meticulously analyzed the results by focusing on their approaches to weighting and evaluating the various sustainability criteria. While both methodologies prioritized economic sustainability (evident from the similar weights that were assigned to 'Ton/kilometer transport unit' and 'Surface area'), subtle differences emerged in their treatment of the environmental and social aspects.

Known for its qualitative judgment capabilities, the MACBETH method appeared to place a slightly greater emphasis on such environmental criteria as 'Atmospheric impact' and 'Water.' This could have been attributed to MACBETH's ability to effectively integrate qualitative assessments, thereby providing a nuanced view of the environmental impacts. On the other hand, the AHP method (with its systematic pairwise comparison technique) offered a structured quantification that tended to amplify the importance of directly measurable criteria such as 'Number of jobs,' highlighting its more quantifiable approach toward assessing the social impacts.

These methodological differences highlighted the inherent analytical perspectives that each tool brought to the decision-making process. MACBETH's qualitative leanings helped us capture broader environmental and social nuances that might have been understated in the purely quantitative analysis of AHP. Conversely, AHP's structured comparisons ensured a rigorous and reproducible quantification of the criteria, making it particularly useful in scenarios where clear measurable outcomes were paramount.

The distinctions between the tools suggest that, while they are both robust for multi-criteria decision-making, their outputs may be best utilized in complementary rather than standalone applications. For instance, employing MACBETH to initially screen sites based on the qualitative environmental and social impacts followed by AHP to finalize those decisions where the quantitative economic and operational data is more pronounced could yield more-balanced and more-comprehensive decision-making outcomes.

Understanding these nuances allows stakeholders to make informed choices about which methodology to employ based on the specific context of a quarry-site evaluation, thus ensuring that both the subtle qualitative aspects and the critical quantitative elements of sustainable site selection are adequately addressed

3.2. Family of Criteria

In assessing the family of criteria for decision-making, a balanced approach could be observed among the three primary dimensions: economic, environmental, and social. According to Table 4, the weights that were assigned to each criterion showed marginal differences in the MACBETH and AHP tools (with economic criteria scoring 38.81 and 38.8%, environmental criteria – 32.17 and 33.1%, and social criteria – 28.99 and 28.1%, respectively). This distribution reflected the nuanced perspectives of decision-makers who recognized the interconnectedness among these elements. The economic criteria received substantial weight, accounting for more than 38% in both models; this reflected the critical importance of cost factors such as transport and the potential for economic output that large-area quarries can offer.

From the decision-makers' standpoint, the economic aspect is a driver of growth; it enhances productivity, ensures the availability of goods and services, and consequently lowers prices. This dynamic not only improves the general well-being of populations but also stimulates job creation, thereby reducing unemployment and boosting purchasing power; this ultimately fosters social empowerment and fulfillment.

Gaining prominence due to heightened ecological consciousness, the environmental dimension has led decision-makers to prioritize the conservation of the environment. Recognizing the escalating costs and extent of environmental degradation, there has been a concerted effort to incorporate environmental stewardship into economic planning. This approach aligns with the principles of sustainable development, emphasizing responsibility, protection, and precaution for balancing developmental needs with ecological preservation. The environmental weights (particularly, the significance assigned to 'Atmospheric impact' and 'Water') highlighted the industry's proactive engagement with environmental management. The consideration of the 'Slope' and 'Visual impact, site safety, and rehabilitation' criteria further exemplified a commitment to minimizing the ecological footprint and ensuring responsible resource utilization.

In the realm of social concerns, decision-makers aim to enhance the quality of life, ensuring dignity and access to fundamental needs like education and healthcare. This focus on addressing poverty, exclusion, and inequality is a stride toward achieving equity and social justice. Such a holistic approach where social and environmental needs are central to decision-making resonates with the evolving concept of sustainable development (as was outlined by [31]). Our findings have illuminated the extractive industry's role as a potential engine for social enhancement. The criteria that were related to the proximity to 'Habitat areas' and the 'Number of jobs' created demonstrated a direct correlation between quarry operations and the socio-economic upliftment of communities, suggesting a sector that is increasingly aware of its societal impact.

The recent decades have seen significant efforts (including legislative reforms and the implementation of various tools) toward protecting the natural environment and guiding sustainable territorial development. The authors of [32] highlighted this shift, noting that these changes had facilitated a more harmonious coexistence between the extractive industry and its surrounding environment. Marked by a commitment to environmental preservation, economic efficiency, and social equity, this progress aims to fulfill the aspirations for sustainable and long-lasting development, thus ensuring the protection of the natural environment against potential pollution and optimizing the extractive activities for future generations.

3.3. Criteria

In the nuanced domain of quarry-site selection, our criteria were meticulously validated against empirical ground studies and consultations with a broad spectrum of stakeholders (including operators, regulatory authorities, employees, and local residents). As was captured in the table and illustrated in Figures 9 and 10, the accompanying results reflect a multi-faceted evaluation process. In these figures, the green areas indicate 'Avoid' zones (where quarrying is not recommended due to the various constraints), the red areas represent 'Strictly favorable' zones (deemed to be most suitable for quarrying based on the multiple favorable criteria), and the remaining uncolored areas are 'Moderately favorable' (requiring further assessment for potential suitability). These zones were defined based on an integrated analysis of criteria such as economic benefits, social impact, and environmental considerations, with each zone's categorization informed by the specific weightings that were derived from our MACBETH and AHP models.

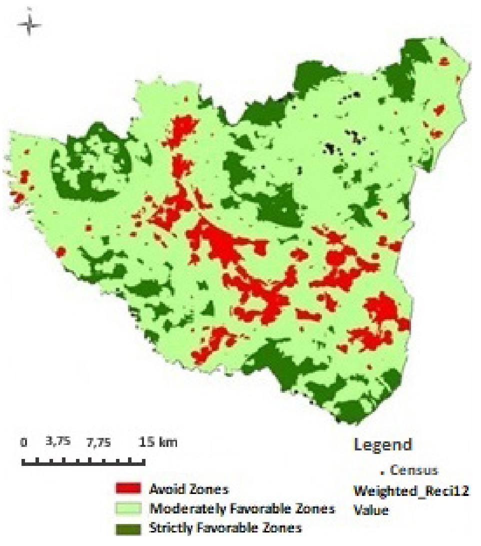

Fig. 9. Classification of quarry-site suitability in Settat Province: 'Avoid', 'Moderately favorable', and 'Strictly favorable' zones using MACBETH Method

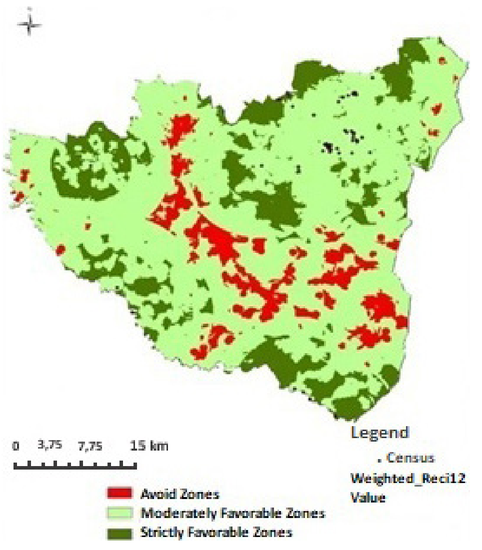

Fig. 10. Classification of quarry-site suitability in Settat Province: 'Avoid', 'Moderately favorable', and 'Strictly favorable' zones using AHP Method

With an average difference of merely 4%, the convergence of the weights between the MACBETH and AHP models signified a robust alignment in the decision-makers' assessments. This alignment is visually represented in the figures, where the spatial distribution of the potential sites is categorized into zones of varying suitabilities: 'Avoid', 'Moderately favorable', and 'Strictly favorable'.

Weighted at 14.20% for MACBETH and 13.1% for AHP, the 'Ton/kilometer transport unit' criterion underscored the economic influence of location on product cost, as the transport expenses escalated with distance. This factor was pivotal for determining the strategic positioning of industrial activities in order to minimize costs, thereby influencing the site selection (as was depicted in the spatial analysis).

With weights of 11.40% for MACBETH and 10.8% for AHP, the 'Surface area' criterion similarly indicated the profitability that was associated with larger sites due to scale economies. This was corroborated by the spatial expanses that are highlighted in the figures (where the larger green patches denote areas of economic interest).

Scoring 9.25% for MACBETH and 8.8% for AHP, the 'Number of jobs' criterion illustrated the social value of the employment opportunities that are provided by the industry, which can serve as a counterbalance to the nuisances that may occur. This is reflected in the figures (where denser quarry zones correlate with local employment potential).

Furthermore, the 'Habitat areas' and 'Atmospheric impact' criteria (with respective scores in the range of 7.3 to 8.61% across both models) demonstrated the environmental considerations of proximity to residential areas and air quality. These are visualized in the figures as areas that are further from the red zones, indicating lesser environmental impacts.

Scoring around 8% for both models, the 'Water' criterion emphasized the essential nature of water conservation – a priority that was amplified by the environmental challenges. With scores near 7%, the 'Roads' criterion reflected concerns over infrastructure strain due to material transportation (as can be seen in those areas that are adjacent to the major transport routes on the maps).

The 'Slope' criterion (of a minimal weight due to the region's flat topography) and the 'Historic monuments, tourist sites' criterion (of a low weight given the quarries' distances from such sites) showed a limited impact in the spatial analysis.

In conclusion, Figures 9 and 10 (at the end of our analysis) provide a visual synthesis of the multi-criteria evaluation, offering a clear hierarchical classification of the quarry sites. The integration of the criteria into the model culminates in a weighted overlay of thematic maps, thus facilitating a strategic approach to quarry-site selection that aligns with sustainable development principles.

3.4. Social and Environmental Implications

The social implications of our research are profound. By factoring in 'Number of jobs' and proximity to 'Habitat areas,' our approach promotes the industry's potential to enhance community welfare. However, it is also crucial to consider the potential for social displacement and cultural impact – particularly when quarrying near heritage sites or communities with deep-rooted connections to the land.

The environmental implications are equally significant. Our criteria weigh heavily on conserving 'Water' and mitigating 'Atmospheric impact,' reflecting a shift toward environmental responsibility. Nevertheless, the actual application of these criteria must navigate the complexities of ecological preservation, including the maintenance of biodiversity and the management of renewable resources.

4. Conclusion

In direct response to our research objectives that were aimed at enhancing the efficiency and sustainability of quarry-site-selection processes, our study demonstrated the efficacy of an integrated MCDA/GIS approach. This method streamlined the quarry-site selection by effectively balancing critical sustainability factors such as environmental impact, economic benefits, and social implications. Specifically, our research objectives sought to evaluate whether a hybrid approach that utilized both MACBETH and AHP within a GIS framework could provide a superior decision-support system when compared to traditional methods. Our findings affirmed these objectives, confirming the hypothesis that a combined MACBETH and AHP model not only enhanced the decision-making accuracy but also offered a more nuanced and comprehensive analysis than when these models were used independently.

Furthermore, our research represents a significant leap forward in the sustainable development of quarry-site selection, presenting a refined MCDA/GIS model that marries the analytical strengths of MACBETH/GIS and AHP/GIS methodologies. Being rigorously applied to Settat Province, this pioneering framework stands as a robust blueprint for identifying quarry sites that harmonize economic, social, and environmental factors. The comprehensive database and thematic maps that we created serve not as merely a decision-making facilitator within Settat but also a scalable tool that is poised for adaptation and application in diverse geographic and regulatory contexts.

The practical application of our model extends beyond its initial context in Settat, offering a systematic approach for assessing quarry-site suitability that can be tailored to specific local conditions in other regions. This adaptability makes our integrated decision-support system a powerful tool for stakeholders who are engaged in strategic planning and sustainability at all levels of industrial operations.

Looking forward, we encourage future research to leverage this model, adapting and refining it to meet local specifics, and expanding the scope of sustainable quarry-site practices worldwide. As global sustainability challenges and priorities evolve, our model will also need to adapt, thus ensuring its effectiveness and applicability in the ever-changing landscape of global industry practices.

In conclusion, the success of our research will ultimately be measured by its adoption and adaptation across various territories – each with unique environmental and socio-economic characteristics. We envision this work as a catalyst for further research and innovation in the field of industrial site-selection and sustainable development, aiming to forge a path where economic growth, social equity, and environmental preservation are jointly achieved. Through continuous exploration and collaborative effort, our model can contribute significantly to sustainable industrial practices globally.

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CRediT Author Contribution

I. A.: conceptualization, methodology, validation, writing – original draft preparation, supervision, project administration.

A. A.: formal analysis, investigation, writing – review and editing, validation.

S. H.: visualization, resources, software.

Declaration of Competing Interest

The authors declare no financial, personal, or professional conflicts of interest related to this research.

Data Availability

The data supporting this study's findings are not publicly available due to legal restrictions.

Use of Generative AI and AI-assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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