Exploring Generative AI for Dynamic Carrying Capacity Assessment in Mountainous and Cave Areas: A Framework Development Approach

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Abstract— This study explores the potential of Generative Artificial Intelligence (GenAI) in developing a dynamic framework for assessing tourism carrying capacities in natural destinations, with a specific focus on mountainous and cave areas in Thailand. The proposed framework, termed SAFER (Sustainable Economic Development, Allocating Resources Optimally, Fostering Community Engagement, Enhancing Visitor Satisfaction, and Resource Conservation), integrates GenAI's advanced capabilities in creating data-driven and adaptive solutions to address the complexities of sustainable tourism management. Unlike traditional AI applications, which emphasize pattern recognition and decision-making, GenAI uniquely enables the creation of predictive and prescriptive tools tailored to specific ecological and cultural contexts. The study employs a mixed-methods approach, involving data collection from 14 pilot sites, stakeholder feedback sessions, and collaborative workshops. These methodologies were critical in refining the SAFER framework and identifying its usability and scalability for diverse tourism settings. By leveraging GenAI's ability to analyze and generate content dynamically, the framework offers innovative strategies to balance tourism growth with environmental conservation and community welfare. Results highlight the SAFER framework's applicability in managing tourism's carrying capacity in sensitive ecosystems, demonstrating how GenAI enhances decision-making processes and visitor management strategies. While the focus of this research is on mountainous and cave regions due to their ecological significance and pressing conservation challenges, the SAFER framework can be adapted to other natural and cultural settings. This study contributes to sustainable tourism research by introducing an adaptable framework that aligns technological innovation with conservation principles, promoting long-term ecological and social well-being. Policymakers, tourism managers, and conservationists can utilize these insights to implement GenAI-driven strategies, fostering resilience and sustainability in tourism management.

Keywords—HCI, Generative AI, Tourism Environmental Carrying Capacity, Natural Environment Area, Sustainable Tourism, Thailand

I. Introduction

Tourism is a significant driver of economic growth and socio-economic benefits, but it also presents environmental and cultural challenges, particularly in ecologically sensitive areas such as mountainous and cave regions. The delicate balance between tourism development and conservation in these areas necessitates effective management strategies for sustainable tourism [1,2].

Traditional sustainable tourism management methods, which often rely on static visitor limits and periodic assessments, struggle to address the dynamic nature of modern tourism [3,4]. This limitation highlights the need for more adaptive and responsive management approaches that can evolve with changing tourist behaviors and environmental conditions.

Advancements in technology, particularly in Artificial Intelligence (AI) and Generative AI (GenAI), offer promising tools for enhancing tourism carrying capacity management. While traditional AI applications focus on optimizing processes and recognizing patterns, GenAI specializes in creating new and original content, such as text, images, videos, and other data forms, using advanced models like Generative Adversarial Networks (GANs) and transformer-based architectures such as GPT and DALL-E. This content-generation capability allows GenAI to produce adaptive, context-sensitive outputs that address dynamic challenges, making it particularly suited for developing tools tailored to specific ecological and cultural contexts. However, the successful integration of these technologies requires careful consideration of human factors and user experience. This is where Human-Computer Interaction (HCI) principles become crucial, ensuring that frameworks leveraging GenAI are not only technologically advanced but also user-friendly and practically applicable, thereby facilitating more adaptive and sustainable tourism management solutions [5].

This paper presents the SAFER framework—Sustainable Economic Development, Allocating Resources Optimally, Fostering Community Engagement, Enhancing Visitor Satisfaction, and Resource Conservation—as an innovative tool for managing tourism carrying capacity in Thailand's mountainous and cave regions. Developed using a mixed-method approach, including expert workshops and user experience studies, the framework emphasizes HCI principles for real-world usability. By integrating HCI-driven development with GenAI capabilities, the study provides a holistic approach to sustainable tourism management, addressing ecological risks and offering practical solutions for policymakers, tourism managers, and stakeholders. [4,5].

II. Literature Review

The management of tourism carrying capacity in sensitive areas, such as mountainous and cave regions, is complex and multifaceted. This section reviews literature on sustainable tourism management, the role of HCI in developing management frameworks, and the potential integration of AI and GenAI in environmental and tourism management. It aims to provide a comprehensive understanding of current methodologies, identify gaps, and highlight the potential of user-centered design approaches to enhance sustainable tourism practices in Thailand's unique natural landscapes.

A. Sustainable Tourism Management and Carrying Capacity

Sustainable tourism, as defined by the World Tourism Organization (UNWTO), focuses on long-term economic viability, social equity, and environmental conservation [6]. Traditional models like the Triple Bottom Line (TBL) approach [7] and the Carrying Capacity model have been foundational in sustainable tourism strategies [8]. However, these models often lack the flexibility to adapt to rapidly changing conditions and user needs.

In mountainous and cave regions, sustainable tourism faces unique challenges, such as soil erosion, habitat destruction, and wildlife disturbance [11]. These areas are ecological and cultural treasures, hosting unique ecosystems, endemic species, and sacred sites. However, increasing tourism threatens these fragile areas with environmental degradation and cultural commodification. Their vulnerability to over-tourism and climate change highlights the urgent need for innovative strategies to balance preservation with local and visitor needs, ensuring their long-term sustainability. The concept of carrying capacity has evolved to include adaptive, data-driven approaches that consider dynamic ecosystems and changing tourist behaviors, addressing the limitations of traditional methods [14,15]. This evolution highlights the need for more user-centric and adaptive management frameworks.

B. The Role of Technology in Tourism Management and Artificial Intelligence in Environmental and Tourism Management

The integration of technology in tourism management has evolved significantly, with HCI playing a crucial role in ensuring these advancements are user-friendly and effective. Initially, IT improved operations with booking systems and electronic guides. Now, more advanced technologies are being implemented, with HCI principles guiding their design and implementation to enhance user experience and management efficiency [16].

Recent studies highlight how HCI-driven design in tourism technologies enriches visitor experiences and streamlines site management. For instance, the development of virtual reality (VR) interfaces for virtual tours of inaccessible sites considers user comfort and intuitive interaction [17,18]. Similarly, the design of IoT device interfaces for monitoring visitor numbers and movement focuses on providing clear, actionable information to management staff, aiding in crowd management and reducing environmental footprints [19].

The advent of AI and GenAI has introduced new possibilities in environmental conservation and tourism management, with HCI playing a critical role in making these complex technologies accessible to tourism stakeholders. AI applications, such as predictive analytics for visitor flow management and AI-driven content generation for personalized guides, are being developed with user-centered design principles to ensure their effectiveness and adoption [4].

Studies have shown that the success of AI and machine learning in predicting visitor flows, environmental impacts, and optimal carrying capacities heavily depends on well-designed user interfaces and interaction models. For instance, machine learning algorithms used to analyze visitor data and predict peak times are most effective when their outputs are presented in intuitive, easy-to-understand formats for tourism managers [20]. The design of AI models for assessing environmental impacts of tourism focuses not just on accuracy, but also on how the information is conveyed to enable proactive conservation measures [2].

HCI research is particularly crucial in realizing AI's potential for dynamic carrying capacity management. The development of interfaces that allow real-time data analysis and predictive modeling to adjust carrying capacity estimates based on current conditions and visitor behavior requires careful consideration of user needs and cognitive processes. This ensures that the sustainable management of natural resources and visitor satisfaction maximization are achieved through systems that tourism managers can effectively use and trust [21].

C. Challenges and Integrative AI Solutions for Sustainable Tourism in Thailand's Natural Landscapes

The sustainable management of tourism within Thailand's distinctive mountainous and cave areas faces multiple challenges, which require innovative, user-centered solutions. These challenges persist despite advancements in AI and GenAI technologies, highlighting the need for an HCI-driven approach to technology integration.

One significant challenge is the infrastructural deficit, particularly in transportation and accommodation [22,23]. Addressing this issue requires not just technological solutions, but interfaces and systems that local operators and officials can easily understand and implement. HCI principles can guide the development of user-friendly tools for infrastructure planning and management, ensuring that technological solutions are accessible and effective for local stakeholders. Environmental concerns, such as waste production and habitat disturbance, pose another major challenge [23,24]. Here, HCI can play a crucial role in developing intuitive monitoring systems and educational interfaces that help both tourists and local communities understand and mitigate their environmental impact.

A critical gap identified is the insufficient inclusion of local communities in decision-making processes and the inequitable distribution of tourism benefits [23,25]. This challenge underscores the importance of developing participatory design approaches and community engagement platforms. HCI methodologies, such as co-design workshops and user research, can ensure that technological solutions are culturally appropriate and meet the needs of local communities. The absence of a dedicated regulatory framework tailored to mountainous and cave environments limits the effectiveness of sustainable tourism management strategies [23,24]. HCI can contribute to this challenge by designing user-friendly policy development and implementation tools, making complex regulations more accessible and easier to enforce.

III. METHODILOGY

This study employs a HCI research approach to develop the SAFER framework for enhancing tourism carrying capacity management in Thailand's mountainous and cave regions, with a focus on integrating GenAI capabilities. The SAFER framework—encompassing Sustainable Economic Development, Allocating Resources Optimally, Fostering Community Engagement and Inclusivity, Enhancing Visitor Satisfaction and Experience, and Resource Conservation and Environmental Protection. This is primarily based on the National Tourism Carrying Capacity Guidelines resulting from our comprehensive main study. While the SAFER framework and GenAI tools can be applied broadly, this study focuses on Thailand's mountainous and cave regions as pilot cases due to their ecological fragility, cultural significance, and tourism pressures. These cases provide insights into the framework's adaptability and scalability for other natural and cultural areas.

Our methodology unfolded in three interconnected phases. Initially, we conducted an exhaustive review of 50 peer-reviewed articles and reports from the past decade, focusing on sustainable tourism, carrying capacity management, and AI applications in tourism [1,2]. This literature review was complemented by collaborative workshops with 15 experts in sustainable tourism and AI technology. These workshops facilitated discussions on current challenges, potential GenAI applications, and the initial framework development.

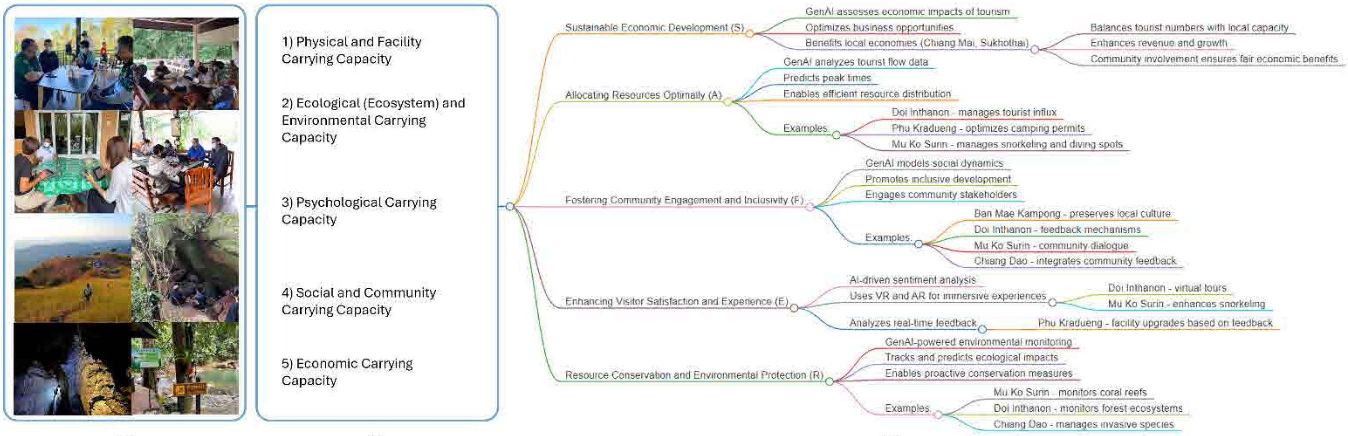
Building on these insights, we collected 79 responses from key stakeholders through surveys to gather their perspectives on sustainable tourism and the use of AI tools. The stakeholder input highlighted concerns such as data security, system complexity, and the need for training in AI techniques, which informed the framework refinement process.

Additionally, we conducted extensive field studies across 14 sampling sites throughout Thailand, including Doi Inthanon National Park, Chiang Dao Wildlife Sanctuary, and various eco-tourism and community sites in Chiang Mai, Mae Hong Son, Sukhothai, Nan, Chanthaburi, Phetchaburi, Tak, Bueng Kan, Ubon Ratchathani, Satun, and Yala. These field studies provided crucial data on local conditions, challenges, and opportunities for sustainable tourism management.

To refine and validate the components of the SAFER framework, we employed HCI methods, particularly a hybrid card sorting technique [26] with 20 tourism management professionals. This process involved creating cards representing potential framework components derived from the national guidelines and our field studies, followed by individual sorting sessions and group discussions [27]. This approach allowed us to align the framework with national guidelines while ensuring its practical applicability.

The final phase focused on a thematic analysis of applying GenAI to evaluate tourism carrying capacity in mountainous and cave areas, structured around the SAFER framework. We synthesized insights from the National Tourism Carrying Capacity Guidelines, our field studies, and the HCI-focused activities to detail the framework. Throughout this process, we maintained a consistent focus on potential applications of GenAI, ensuring that the framework leverages advanced AI capabilities while remaining practical for tourism management stakeholders.

This comprehensive, HCI-centered approach allowed us to develop the SAFER framework as an extension of the National Tourism Carrying Capacity Guidelines, addressing the complex challenges of sustainable tourism management in Thailand's unique landscapes while integrating cutting-edge GenAI technologies. The resulting framework, as illustrated in Fig. 1, demonstrates the alignment between our field study findings, national guidelines, and the SAFER themes, providing a robust tool for enhancing tourism carrying capacity management through GenAI applications [4,5].



(a) (b) (c)

Fig.1. Alignment of the SAFER Framework with National Tourism Carrying Capacity Guidelines

IV. Result and Discussion

This section presents a combined quantitative and thematic analysis of applying GenAI to evaluate tourism carrying capacity in Thailand's mountainous and cave areas, utilizing the SAFER framework. The findings, as shown in Fig. 1, include: (a) data collected from field trips, interviews, and questionnaire studies, (b) insights derived from Carrying Capacity Criteria, and (c) SAFER framework themes. These results are based on evaluations conducted at 14 sampling sites across Thailand, aligning the framework with national tourism guidelines and SAFER components.

The study surveyed 79 participants to assess their familiarity with GenAI and its potential applications in tourism management. The respondents, as summarized in Table 1, represented diverse demographic groups and reported moderate familiarity with GenAI, with a mean score of 3.85 out of 5 (SD = 1.06). Regarding the perceived potential of GenAI to enhance tourism management, the mean score was 3.72 (SD = 0.90), indicating a generally positive outlook. Participants rated GenAI's ability to improve environmental data management highly, with a mean score of 3.83 (SD = 0.84). Real-time data analysis received the highest mean score of 4.05 (SD = 0.80), underscoring its perceived importance in tourism contexts. Additional applications, such as managing tourist congestion and assessing environmental impacts, also garnered favorable ratings, with mean scores of 3.65 (SD = 0.95) and 3.73 (SD = 1.03), respectively. These findings highlight a strong inclination toward utilizing GenAI for dynamic and sustainable tourism management solutions while addressing critical operational needs.

TABLE I: QUANTITATIVE RESULTS TABLE

Item	**Mean (M)**	**Standard Deviation (SD)**	**Percentage (%)**
Familiarity with GenAI	3.85	1.06	77
GenAI's potential in tourism management	3.72	0.9	74.4
GenAI for environmental data management	3.83	0.84	76.6
Managing tourist congestion	3.65	0.95	73
Assessing environmental impact	3.73	1.03	74.6
Real-time data analysis	4.05	0.8	81

The following findings integrate expert perspectives, thematic analyses, and examples to explore how advanced AI technologies could enhance sustainable tourism practices, even though GenAI is not currently implemented in these areas. Below is a summary of key insights categorized under SAFER framework themes:

A. Sustainable Economic Development (S)

While GenAI is not yet implemented in Thailand's mountainous and cave regions, stakeholders recognize its potential to assess and predict tourism's economic impacts. In Chiang Mai and Sukhothai, local business owners envision using GenAI to forecast tourist influx and optimize resource distribution, potentially boosting profitability and sustainability. A hotel owner in Chiang Mai remarked, *"Accurate peak season predictions would help us prepare better and reduce waste, significantly improving profitability."*

Tourism officials see GenAI as a tool to balance tourist numbers with local capacity, enhancing revenue and supporting business growth. A community leader in Sukhothai highlighted its role in empowering local voices in tourism planning, ensuring fair economic benefits for all. Stakeholders believe GenAI-driven processes could foster community ownership, boost the local economy, and promote sustainable tourism practices.

This enthusiasm reflects a growing recognition of the need to balance economic growth with community well-being and resource conservation in Thailand’s sensitive regions. Stakeholders remain eager to explore GenAI’s integration into future tourism management strategies.

B. Allocating Resources Optimally (A)

Stakeholders recognize GenAI’s potential to optimize resource allocation and infrastructure management, even though it is not yet implemented in Thailand's mountainous and cave regions. Tourism officials and managers see its ability to analyze tourist flow data and predict peak times as a way to enhance efficiency and reduce congestion.

At Doi Inthanon National Park, a ranger noted, *"GenAI could be a game-changer by helping us predict and manage congestion at hotspots like the summit, significantly improving visitor experiences while protecting the* *environment."* Similarly, officials at Phu Kradueng National Park highlighted its potential to optimize camping permit distribution and trail management. In marine environments like Mu Ko Surin National Park, GenAI could prevent overcrowding and protect delicate ecosystems by monitoring visitor numbers and predicting peak times.

Stakeholders envision AI-driven simulations aiding in infrastructure design, such as allocating parking spaces and rest areas, which could significantly enhance operational efficiency. This enthusiasm reflects the importance of integrating advanced solutions like GenAI to ensure sustainable tourism practices that improve visitor experiences while preserving natural and cultural heritage.

C. Fostering Community Engagement and Inclusivity (F)

While GenAI is not yet used in Thailand's tourism sector, local communities and officials are optimistic about its potential to enhance inclusivity and fairer tourism development. At Ban Mae Kampong, a community leader noted, *"Smart tools could help us understand how tourism affects us, enabling better choices that align with our way of life."* Similarly, a Doi Inthanon park manager emphasized how AI could enhance collaboration with locals by analyzing feedback and predicting tourism impacts to balance the needs of both visitors and communities.

In marine parks like Mu Ko Surin, conservationists highlighted the value of AI in preventing overcrowding and addressing potential problems early to maintain cultural harmony. At Chiang Dao Wildlife Sanctuary, an official suggested that GenAI could anticipate how tourism might impact traditions, ensuring plans respect local lifestyles.

Though GenAI is not currently in use, stakeholders believe it could make tourism planning more inclusive, respecting cultural values and local needs. This forward-looking approach underscores the growing awareness of balancing tourism with community well-being and cultural preservation in Thailand’s unique and sensitive natural areas [2, 4, 5].

D. Enhancing Visitor Satisfaction and Experience (E)

Although advanced AI and immersive technologies are not yet implemented in Thailand's tourism sites, visitors and park managers are optimistic about their potential to enhance experiences. At Doi Inthanon National Park, a visitor suggested that virtual reality could allow access to restricted areas without environmental disturbance, offering a "sneak peek without leaving footprints." Similarly, a ranger at Mu Ko Surin Marine National Park envisioned augmented reality enhancing snorkeling trips by displaying fish names in real time, fostering appreciation for marine ecosystems.

At Phu Kradueng National Park, a manager highlighted the value of AI in analyzing visitor feedback: *"A smart system that reads reviews could quickly identify what visitors love and what needs improvement."* A tourism official in Chiang Mai added that AI could personalize experiences, providing tailored information to connect visitors with culture and nature.

These creative ideas reflect growing interest in using technology to make tourism more fun, educational, and personalized, while protecting natural and cultural heritage. The enthusiasm underscores the belief that thoughtful integration of modern technology can benefit both visitors and local communities [1, 2, 3, 4, 5].

E. Resource Conservation and Environmental Protection (R)

While GenAI-powered systems are not yet used in Thailand's natural parks, park rangers and environmental experts see their potential to protect ecosystems while supporting tourism. At Mu Ko Surin Marine National Park, a coral reef expert envisioned *"smart computers monitoring coral reefs to detect over-visitation and prevent damage before it happens."* Similarly, a biologist at Doi Inthanon highlighted GenAI’s potential to track wildlife movements and tourist locations, ensuring minimal disturbance to animals during sensitive periods like breeding seasons.

In Chiang Dao Wildlife Sanctuary, a park manager proposed using GenAI as an early warning system for invasive species, preventing harm to native ecosystems. A volunteer at Phu Kradueng National Park emphasized the broader perspective GenAI could offer: *"It’s like a crystal ball, helping us understand the connections in nature and how our actions affect them."*

These insights reflect enthusiasm for AI as a tool to balance tourism with nature protection. By monitoring ecosystems and predicting impacts, GenAI could help maintain ecological health while enabling responsible tourism [1, 2, 4]. Advanced AI platforms, such as Amazon Bedrock and TensorFlow, could analyze visitor data, predict peak times, and optimize resource distribution, while tools like ChatGPT and Claude could enhance community engagement and visitor experiences through real-time insights and immersive technologies [29, 31, 32, 34]. This potential underscores the role of AI in ensuring sustainable tourism management for Thailand’s unique natural landscapes.

Creative tools such as Gemini and Dall-E could support VR/AR content creation, potentially generating interactive and immersive tourist experiences that enhance visitor engagement, promote conservation awareness, and provide detailed information [30,33]. Collectively, these applications could facilitate data-driven decision-making, helping businesses and authorities prepare for peak seasons, allocate resources efficiently, and align management strategies with dynamic ecosystems and evolving tourist behaviors. While these technologies are not yet implemented, their potential applications align with the goals of sustainable tourism development in Thailand's unique natural landscapes [29,30,31,32,33,34].

CONCLUSION AND LIMITATION

This study explores the potential of GenAI in managing tourism carrying capacity in Thailand's mountainous and cave regions through the SAFER framework. While GenAI is not currently implemented, stakeholders show enthusiasm for its future applications in sustainable tourism management. The SAFER framework, developed through field studies and stakeholder engagement, provides a structured approach for potential GenAI integration, envisioning support for data-driven decision-making and efficient resource allocation. However, potential GenAI implementation faces challenges including data dependency, integration complexities, cultural sensitivity, user adoption, and ethical concerns. Addressing these would require advanced technology, stakeholder engagement, community involvement, and robust regulations. The SAFER framework and GenAI tools developed in this study offer significant potential for adaptation to diverse natural and cultural tourism contexts beyond mountainous and cave regions. By leveraging their flexibility and data-driven capabilities, these tools can be tailored to address the unique challenges of coastal areas, urban heritage sites, and other sensitive environments. Future studies should explore the scalability of the framework across various settings, refining its components to meet region-specific needs while maintaining its core principles of sustainability, community engagement, and visitor satisfaction.

Future research should focus on practical pilot implementations, developing culturally sensitive AI models, studying long-term impacts, and investigating ethical implications, particularly regarding data privacy and the digital divide. Collaboration among experts, policymakers, and communities is crucial to balance GenAI applications with traditional practices and local knowledge. Although this study highlights the potential of Generative AI in tourism management, the lack of pilot testing limits its real-world validation. Future research will focus on implementing and testing the framework to assess its practical effectiveness and adaptability. In conclusion, while GenAI offers promising potential for enhancing sustainable tourism management in Thailand's natural landscapes, its implementation requires careful consideration and further study to ensure the promotion of economic viability, social equity, and environmental conservation.

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