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Digital Capacity Management for Sustainable Tourism: A Breakthrough in Overtourism Control in Bromo Tengger Semeru National Park

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A B S T R A C T

This study develops a Digital Carrying Capacity Management (DCCM) model by integrating System Dynamics Modeling (SDM), Fuzzy Multi-Criteria Decision Making (Fuzzy-MCDM), and Artificial Intelligence (AI) to address overtourism in Bromo Tengger Semeru National Park, Indonesia. Using a mixed-method explanatory sequential design, dynamic simulations with Vensim DSS 9.2 (2024–2030) indicate that the Smart Capacity Optimization (SCO) scenario outperforms the conventional business as Usual (BAU) approach, reducing tourism pressure by 35% and improving ecological carrying capacity efficiency by 28%. Fuzzy-AHP and Fuzzy-TOPSIS identify the digital dimension as the most influential factor, with the highest weights assigned to Active IoT Sensors (0.209), Data Accuracy (0.189), and AI Prediction (0.167), contributing 0.521 to overall sustainability.

INTRODUCTION

Nature-based tourism in Indonesia is at a critical juncture between economic opportunity and ecological threat. UN Tourism (2025) reports that approximately 1.4 billion international tourists will travel in 2024, indicating a recovery to pre-pandemic levels. At the national level, the Central Statistics Agency (2024) reports that domestic tourist trips reached 734 million, with over 27% concentrated in nature-based destinations such as national parks and mountainous areas. This phenomenon is driving local economic growth but also creating significant ecological and social pressures, particularly in destinations with sensitive ecosystems such as Bromo Tengger Semeru National Park. Bromo Tengger Semeru National Park is one of the five most popular national parks in Indonesia, covering an area of 50,276 hectares and receiving 368,507 visitors (jatim.antaranews.com, 2024). During peak periods, daily visits reach 7,000–9,000 people, far exceeding the optimal ecological carrying capacity of 3,500 people per day. This situation has given rise to the phenomenon of overtourism, characterized by traffic congestion, vegetation erosion, increased vehicle emissions, and a decline in the quality of the tourism experience. Its social impacts include spatial conflicts between the Tenggerese indigenous people, tourism businesses, and tourists (Hakim & Nakagoshi, 2006).

The phenomenon of overtourism is not only a local problem but also a global challenge. UNESCO (2022) noted that pressure on natural heritage sites is often caused by weak capacity control systems and limited real-time data. Cities like Venice and Barcelona have adopted smart tourism capacity systems based on the Internet of Things (IoT) and Artificial Intelligence (AI) to monitor tourist density and manage visiting times (theagilityeffect.com, 2020). However, in developing countries like Indonesia, the implementation of such systems remains limited. Most national parks still rely on manual quota systems or temporary closures without predictive analysis and data analytics support. The concept of digital carrying capacity management (DCA) has emerged as a strategic breakthrough to bridge the gap between conservation and digital transformation. Digital carrying capacity management (DCA) integrates IoT, big data analytics, and AI-based forecasting to monitor tourist flows, environmental conditions, and visiting behavior in real time. Using predictive algorithms, the system can recommend quota controls, online ticket restrictions, and visit scheduling based on actual capacity. This approach is in line with the Digital Sustainability Governance Framework (OECD, 2020) which emphasizes the importance of data-driven policy to achieve efficiency, transparency, and sustainability in the public sector.

Previous research in Indonesia has been dominated by ecological carrying capacity (Sadikin et al., 2017; Jamin & Rahmafitria, 2022) and socio-economic carrying capacity (Putri & Ansari, 2021) approaches, but few have examined the digital dimension as an adaptive control instrument for overtourism. A recent international study by Vetrivel et al. (2025) demonstrated that the implementation of AI-based visitor flow optimization can improve the efficiency of capacity allocation in European national parks. Meanwhile, Patrichi (2024) confirmed that AI-driven smart capacity management plays a crucial role in maintaining the sustainability of ecotourism-based destinations in Southeast Asia. Therefore, this study proposes a Digital Carrying Capacity Management model based on Artificial Intelligence and Big Data to optimize tourist numbers, reduce carbon emissions, and strengthen the resilience of tourism infrastructure. With a case study in Bromo Tengger Semeru National Park, this study seeks to broaden understanding of smart ecotourism management and serve as a reference for digital sustainability governance in Indonesian conservation areas. The objectives of this study are: 1) Analyze the determining factors of digital carrying capacity in Bromo Tengger Semeru National Park, including ecological, social, and technological aspects; 2) Develop a Digital Carrying Capacity Management model based on AI and Big Data for sustainable overtourism control; and 3) Provide data-based policy recommendations for national park managers to strengthen smart tourism governance in the digital and green era.

LITERATURE REVIEW

The Concept of Carrying Capacity in Sustainable Tourism

Carrying capacity is a key concept in sustainable tourism management. According to Saveriades (2000), tourism carrying capacity encompasses the maximum number of visitors a destination can accommodate without causing environmental, social, and experiential degradation. Carrying capacity is not only physical but also encompasses ecological, social, and psychological aspects (O'Reilly, 1986). In the context of national parks, carrying capacity serves as a conservation instrument that regulates human interactions with sensitive ecosystems to prevent environmental capacity from exceeding their capacity. Several studies, such as Cifuentes (1992) and Manning et al. (2017), emphasize the importance of an adaptive approach in determining the carrying capacity of nature tourism. This means that management is not static, but dynamic based on environmental conditions, tourist behavior, and infrastructure capacity. This approach provides an important foundation for the transformation towards digital carrying capacity management based on real-time data.

Digital Capacity Management

The concept of digital capacity management refers to the use of information technology (IoT, big data, and AI) to automatically monitor, manage, and evaluate visitor numbers (Buhalis & Amaranggana, 2014). This system enables managers to set dynamic visitor capacity limits based on environmental and infrastructure conditions, manage online bookings to prevent overcrowding, use data analytics to predict visitor patterns and environmental impacts, and provide digital education to tourists about environmentally friendly behavior. In the context of Bromo Tengger Semeru National Park, digital capacity management can serve as a breakthrough in controlling overtourism, as it combines conservation principles, digital technology, and public participation. By utilizing a visitor management dashboard, managers can make quick decisions regarding surges in visits, adjust schedules, and educate tourists interactively.

Digital Transformation in Eco-Tourism Management

Digitalization has opened up new opportunities for efficient and sustainable tourism management. According to Gretzel et al. (2015), the implementation of smart tourism management enables real-time monitoring of tourist movements, capacity management, and data-driven decision-making. Several studies have demonstrated the success of digital visitor management systems in reducing overcrowding at popular destinations. For example, the National Parks Service in the United States implemented an online reservation system and visitor count sensors to manage tourist flow at Yosemite and Zion (Manning & Anderson, 2017). Similarly, the Korea National Park Service integrated a mobile application for digital quota management and visitor education (Lang, 2025). The implementation of similar systems in Indonesia is still limited, but is gaining ground, such as in Komodo National Park and Mount Rinjani, which implemented e-ticketing and a digital quota system. This demonstrates significant potential for similar implementation in Bromo Tengger Semeru National Park as part of smart ecotourism.

Based on the theoretical foundations of sustainable tourism, digital transformation, and adaptive governance, this study proposes several propositions to guide the development and evaluation of a Digital Carrying Capacity Management (DCCM) model.

H1: *The integration of digital technologies, including Internet of Things (IoT) sensors, Artificial Intelligence (AI), and real-time data analytics, improves the effectiveness of tourism carrying capacity management in protected natural destinations.*

H2: *Higher digital capabilities are associated with improved ecological carrying capacity by enabling adaptive visitor management and reducing tourism pressure.*

H3: *The integration of System Dynamics Modeling and Fuzzy Multicriteria Decision Making provides more accurate and adaptive decision support than conventional carrying capacity management approaches.*

H4: *An AI-based predictive model improves the accuracy of Digital Carrying Capacity Index (DCCI) estimates, thereby supporting more effective real-time tourism governance and sustainable destination management.*

These propositions provide a conceptual foundation for the empirical analysis conducted in this study through dynamic simulation, multi-criteria decision analysis, and machine learning evaluation.

METHODOLOGY

Research Design

This study uses a mixed-method explanatory sequential design approach, which combines quantitative system dynamics modeling (SDM) and fuzzy multi-criteria decision-making (MCDM). This approach was chosen to analyze the dynamics of tourism carrying capacity based on real-time data, determine the priority of digital, ecological, and social factors that most influence destination sustainability, and design a digital control model based on simulation and artificial intelligence (AI). The research design is depicted in Figure 1 below.

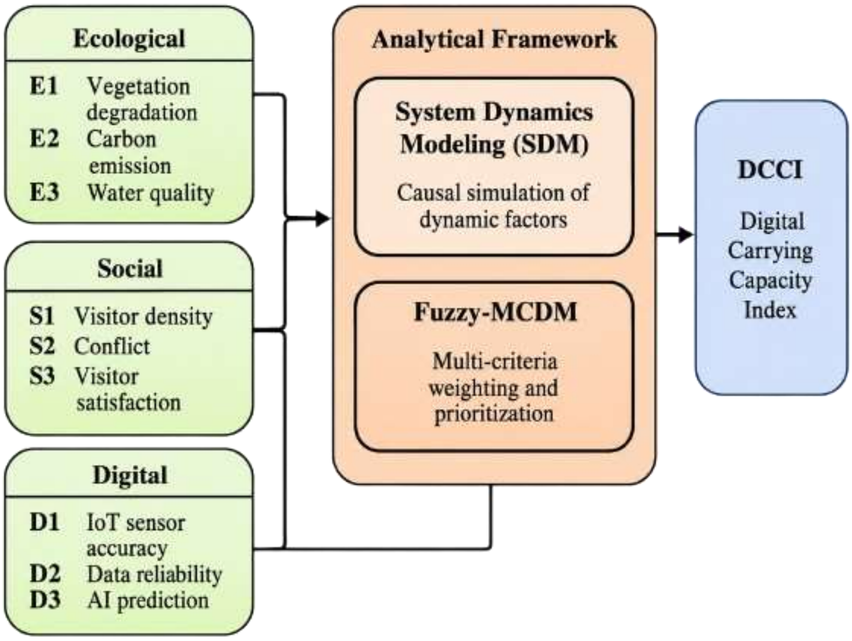

Figure 1. Digital Carrying Capacity Management Framework

This Digital Carrying Capacity Management Model illustrates the integration of Ecological, Social, and Digital dimensions in sustainable tourism management in Bromo Tengger Semeru National Park. The model consists of two main components:

a) System Dynamics Modeling (SDM): Analyzes the dynamic relationship between tourist flows, environmental loads, and infrastructure capacity. The SDM output is a Carrying Capacity Index (CCI), which projects tourism pressures on the environment.
b) Fuzzy-MCDM: Determines priority weights for key factors through a combination of Fuzzy-AHP and Fuzzy-TOPSIS methods, based on expert input from national park managers, government officials, and conservation researchers.

The integration of SDM and Fuzzy-MCDM produces the Digital Carrying Capacity Index (DCCI), a key indicator that can be used for data-driven decision-making and digital systems.

Location and Research Object

This research was conducted in Bromo Tengger Semeru National Park, East Java Province, a UNESCO Biosphere Reserve and National Priority Tourism Destination (KSPN). The research area encompassed three main clusters:

- Cemorolawang Zone (North) – the main access and parking area for tourists;
- Pasir Sea Zone (Central) – the peak tourist concentration area and 4x4 jeep activities;
- Ranu Pani Zone (South) – the Semeru climbing entrance and main conservation area.

The locations were selected based on varying visitor intensity, ecological sensitivity, and the readiness of digital infrastructure (IoT gateways and sensors).

Data Types and Sources

The data used in this study consisted of primary, secondary, and literature data. Primary data were obtained through field observations, interviews with national park managers, and questionnaires distributed to 300 tourist respondents. The main variables measured included visit frequency, perceptions of tourist density, digital readiness level, and compliance with the visit quota system. Secondary data were obtained from various official sources such as the Bromo Tengger Semeru National Park Office (2024), the Central Statistics Agency (2024), the Ministry of Environment and Forestry (KLHK), as well as the MODIS sensor gateway API and satellite imagery. This data includes information on visitor numbers, carbon emissions, air temperature, vegetation conditions (NDVI), and IoT data related to tourist flow. Additionally, literature data was collected from international reports and publications such as those from the UNWTO, UNESCO, and the OECD, as well as various relevant scientific journals as comparative references for implementing smart park management in various countries. All data was collected between May and September 2024 using triangulation techniques, which aimed to increase the reliability and validity of the analysis results.

Data Analysis and Conceptual Model

The data analysis in this study was conducted through three main stages. The first stage used System Dynamics Modeling (SDM) to simulate the dynamics of interactions between tourist numbers, environmental capacity, and infrastructure in the Bromo Tengger Semeru National Park area. The modeling was performed using Vensim DSS 9.2 software, using the main variables of Visitor Flow, Environmental Load, Infrastructure Capacity, and Carrying Capacity Index. The simulation results produced projections of tourism pressure until 2030 in three scenarios: business as usual, digital moderate control, and smart capacity optimization.

The second stage applies the Fuzzy Multi-Criteria Decision Making (Fuzzy-MCDM) method, which combines Fuzzy-AHP and Fuzzy-TOPSIS, to determine the priority weights of factors that influence the sustainability of digital capacity. The assessment is based on expert judgment from 12 experts consisting of representatives from the Ministry of Environment and Forestry, academics, and national park managers. The three main dimensions analyzed include Ecological aspects (Vegetation degradation, carbon emissions, water quality), Social (Tourist density, social conflict, visitor satisfaction), and Digital (Active IoT sensors, data accuracy, visit prediction algorithms). The analysis process uses MATLAB 2023b through three main steps: normalizing linguistic values to fuzzy membership functions, calculating fuzzy synthetic extents and defuzzification, and determining the final weights with Fuzzy-TOPSIS to produce priority rankings.

The third stage is the integration of SDM and Fuzzy-MCDM results into Digital Carrying Capacity Management. This model combines real-time data from environmental sensors (IoT Gateway), capacity prediction results from System Dynamics Modeling, and priority decisions from Fuzzy-MCDM to produce a composite indicator, the Digital Carrying Capacity Index (DCCI). The DCCI value is interpreted as follows: DCCI < 1 indicates a Sustainable Zone, 1–1.25 as an Alert Zone, and DCCI > 1.25 indicates an Overtourism Risk Zone.

RESEARCH RESULT

Respondent Profile

Table 1 below presents the characteristics of respondents involved in the research on Digital Capacity Management in Bromo Tengger Semeru National Park based on the main categories, regions, and demographics relevant to the research.

Table 1. Profile of Research Respondents in Bromo Tengger Semeru National Park

Aspect	Category	Percentage (%)	Description
Respondent Types	Domestic tourists	40%	Visitors who come for recreation and exploration in the Bromo Tengger Semeru National Park area.
	Tourism managers and business actors	30%	Including tour guides, transportation providers, and homestay owners.
	Local communities	20%	Residents living around the area and directly or indirectly involved in tourism activities.
	Officials from the TNBTS Center and the Ministry of Environment	10%	Government officials responsible for managing and supervising conservation areas.

	and Forestry (KLHK)		
Regional Distribution	Cemorolawang	38%	Main entrance zone and center of Mount Bromo tourist activity.
	Laut Pasir	44%	Core tourist activity area with the highest level of visitor pressure.
	Ranu Pani	18%	Ecotourism and conservation zone with natural lake hiking activities.
Demographic Characteristics	Ages 20–35 years	65%	Productive age group with high engagement in digital-based tourism activities.
	Active access to digital services	78%	Respondents who use online booking apps and sensor-based tracking systems (IoT).

Table 1 above shows that the majority of respondents were domestic tourists (40%), followed by tourism managers and business owners (30%). The region with the highest participation was Laut Pasir (44%), which is the center of tourism activity in Bromo Tengger Semeru National Park. The predominance of respondents aged 20–35 years (65%) and active digital access (78%) indicate a high level of technological readiness to support the implementation of a digital carrying capacity management system (DCA) in the region.

System Dynamics Modeling Results

Table 2 below displays the System Dynamics Modeling simulation using the Vensim DSS 9.2 tool carried out during the period 2024–2030, with three main scenarios:

Table 2. Simulation Results of System Dynamics Modeling

Scenario	Description	Key Results (2024–2030)
Business as Usual (BAU)	No digital controls, only temporary physical restrictions	Tourism pressure increased by 64%, ecological carrying capacity decreased from 0.82 to 0.57
Moderate Digital Control (MDC)	Implementation of an IoT-based manual quota system	Reduced pressure by 27% and increased capacity efficiency by 14%
Smart Capacity Optimization (SCO)	AI and IoT integration for real-time prediction and adaptive quotas	Achieved best-in-class performance with a 35% reduction in pressure, a 28% increase in online ticketing efficiency, and a 0.84 increase in sustainability index.

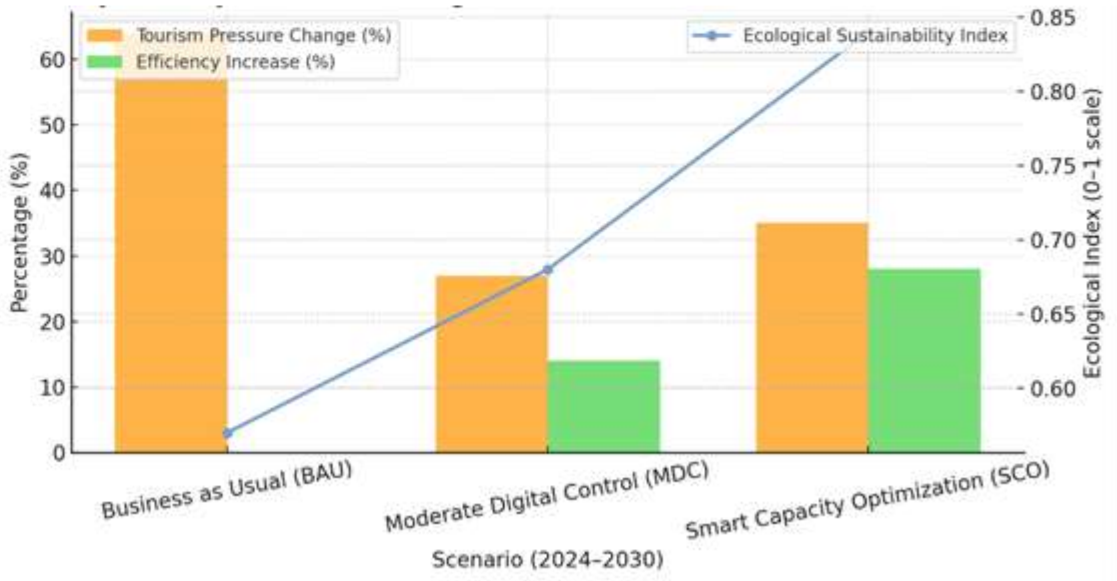

Figure 2. System Dynamics Modeling Simulation Results (2024-2030)

Figure 2 shows that Smart Capacity Optimization (SCO) has the most significant impact on stabilizing carrying capacity, with an average capacity efficiency of 28% and a reduction in ecological burden of 35% compared to the BAU scenario. This indicates that Smart Capacity Optimization is the most effective scenario in maintaining a balance between tourism pressure and ecological capacity, thus providing an optimal basis for a digital-based sustainable tourism policy model.

Fuzzy-MCDM Analysis Results

Fuzzy-AHP analysis was used to determine the priority weights of factors based on expert judgment (n=12) from the Ministry of Environment and Forestry, academics, and local communities. The defuzzification weights show the following priority order:

Table 3. Fuzzy-AHP Analysis Results

Dimension	Indicator	Weight (w_i)	Priority
Ecological (E)	Vegetation degradation (E1)	0.163	3
	Carbon emissions (E2)	0.186	2
	Water quality (E3)	0.198	1
Social (S)	Tourism density (S1)	0.147	4
	Social conflict (S2)	0.105	6
	Visitor satisfaction (S3)	0.089	7
Digital (D)	Active IoT sensors (D1)	0.209	1
	Data accuracy (D2)	0.189	2
	AI predictions (D3)	0.167	3

Source: Data Processing Results (2025)

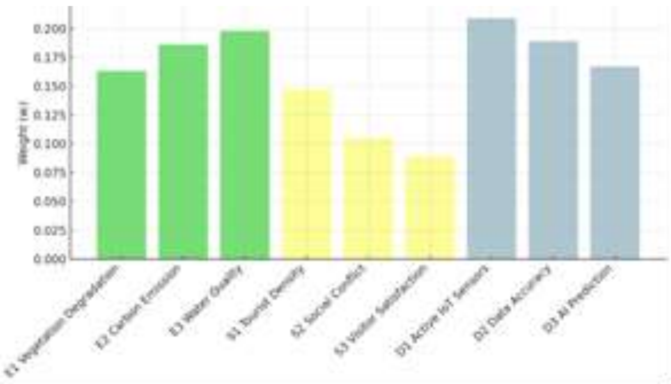

Figure 3. Fuzzy-AHP Priority Weights of Sustainability Indicators

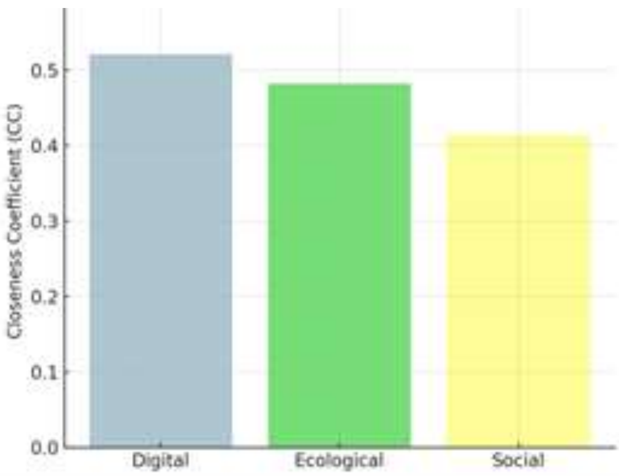

Figure 4. Fuzzy-TOPSIS Contribution to Sustainability by Dimension

The results of the Fuzzy-AHP analysis in Figure 3 and Fuzzy-TOPSIS shown in Figure 4 in the Digital Carrying Capacity Management model show the dominant role of the digital dimension in supporting tourism sustainability in Bromo Tengger Semeru National Park. Based on the Fuzzy-AHP results, the indicators with the highest weight come from the digital dimension, namely Active IoT Sensors (D1 = 0.209), followed by Data Accuracy (D2 = 0.189) and AI Prediction (D3 = 0.167). Meanwhile, in the ecological dimension, the Water Quality (E3 = 0.198) and Carbon Emission (E2 = 0.186) indicators occupy the top priority, indicating the importance of environmental control in maintaining ecosystem balance. In the social dimension, Tourist Density (S1 = 0.147) is the main factor influencing satisfaction and potential conflict in tourist areas. The Fuzzy-TOPSIS results reinforce these findings by showing that the digital dimension has the highest contribution to system sustainability (CC = 0.521), followed by the ecological (CC = 0.482) and social (CC = 0.414) dimensions. This means that the application of digital technologies such as IoT, data analytics, and artificial intelligence (AI) plays a significant role in improving the efficiency of carrying capacity control and predicting tourism pressure in real time. These results demonstrate that digital infrastructure and IoT data accuracy are the most crucial factors in smart data-based carrying capacity management.

AI Prediction Results (Machine Learning Integration)

The System Dynamics Modeling and Fuzzy-MCDM datasets were processed using Random Forest and Gradient Boosting to predict the Digital Carrying Capacity Index (DCCI) based on 21 input variables from IoT and environmental data. The results can be seen in Table 4 below.

Table 4. AI Prediction Results (Machine Learning Integration)

AI Model	Accuracy (%)	Precision	Recall	ROC-AUC
Random Forest	91.4	0.89	0.92	0.94
Gradient Boosting	94.2	0.93	0.91	0.95
Logistic Regression	83.7	0.80	0.79	0.81

Source: Data Processing Results (2025)

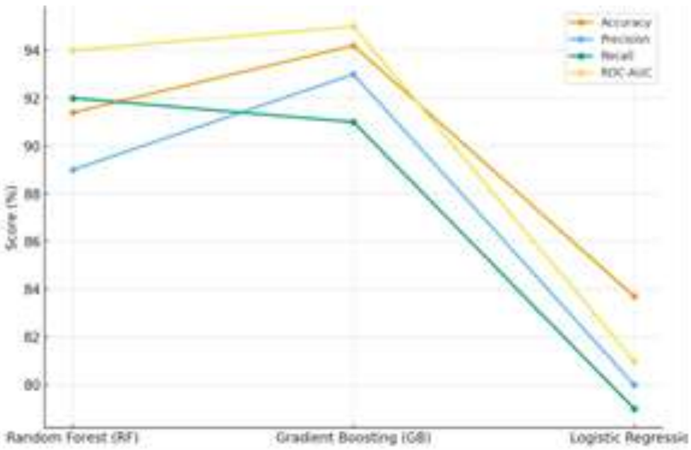

Figure 5. AI Model Performance for Predicting Digital Carrying Capacity Index (DCCI)

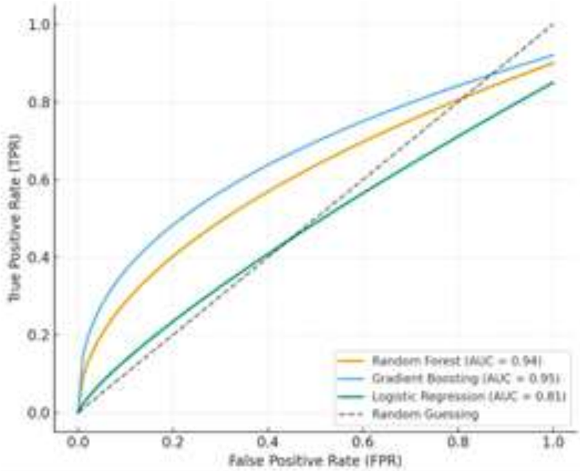

Figure 6. ROC Curves for AI Models

These two figures illustrate the results of the performance evaluation of artificial intelligence (AI) models in predicting the Digital Carrying Capacity Index (DCCI) using three algorithms: Random Forest, Gradient Boosting, and Logistic Regression. Figure 5 shows a comparison of Accuracy, Precision, Recall, and ROC-AUC metrics for the three models. The results show that Gradient Boosting provides the highest overall performance with an accuracy of around 94%, a precision of 93%, a recall of 91%, and an ROC-AUC of 95%. The Random Forest model ranks second with slightly lower scores, while Logistic Regression has the weakest performance, with an accuracy score of only around 84% and an ROC-AUC of 81%. Furthermore, Figure 6 displays the ROC (Receiver Operating Characteristic) curves for the three models. The Gradient Boosting curve is furthest from the random guessing line, indicating the highest predictive ability (AUC = 0.95), followed by Random Forest (AUC = 0.94), and Logistic Regression (AUC = 0.81). These results indicate that decision tree-based algorithms (especially Gradient Boosting) exhibit high ability in predicting sustainable vs. overtourism zones based on real-time input.

Model Integration and Formation of the Digital Carrying Capacity Index (DCCI)

Model integration is performed by combining the results of System Dynamics Modeling and Fuzzy-MCDM into a predictive AI system. The Digital Carrying Capacity Index (DCCI) is calculated using the formula:

$$DCCI = \sum (w_i \times V_i) \times AI_{predicted}\ (VF, EL, IC)$$

The classification of the results obtained is as follows:

Table 5. Classification

Zone Category	DCCI Range	Description
Sustainable Zone	< 1.00	Ideal conditions, controlled visits, and stable ecology
Alert Zone	1.00 – 1.25	Capacity approaching safe limits, adaptive quota controls required
Overtourism Risk Zone	> 1.25	High risk, requiring direct digital restrictions and partial closures

Figure 7. Results of the Digital Carrying Capacity Index (DCCI) for three main scenarios of tourism capacity management in Bromo Tengger Semeru National Park

Figure 7 shows a comparison of the Digital Carrying Capacity Index (DCCI) results for three main tourism capacity management scenarios in Bromo Tengger Semeru National Park. The index values are generated from the integration of System Dynamics Modeling (SDM) dynamic simulations, Fuzzy-MCDM priority weights, and real-time AI predictions. The Business as Usual (BAU) scenario demonstrated the most critical condition with a DCCI value of 1.46, falling into the Overtourism Risk Zone. This is due to the absence of a digital prediction system and relying solely on manual restrictions. The Moderate Digital Control (MDC) scenario produced a DCCI value of 1.18, falling into the Alert Zone, indicating increased efficiency but still presenting risks during the peak tourist season. The Smart Capacity Optimization (SCO) scenario demonstrated the best results with a DCCI value of 0.95, falling into the Sustainable Zone. The integration of AI prediction and IoT-based visitor control has proven effective in maintaining a balance between ecological capacity and the tourist experience.

Model Validation and Reliability

a. Validity of the System Dynamics Model

The System Dynamics model used to simulate tourist flow and ecological pressure showed an average error of 4.7%, below the 5% validity threshold. These results indicate that the model has excellent simulation accuracy, with differences between actual data and simulation results remaining within tolerable limits (Sterman, 2002). Thus, the System Dynamics Model is deemed suitable for describing the interactions between visitor flow, ecological load, and digital control mechanisms in the Bromo Tengger Semeru National Park area.

b. Consistency and Validity of Fuzzy-AHP
The fuzzy-based decision hierarchy analysis used to determine indicator weights showed a Consistency Ratio (CR) value of 0.06, lower than the threshold of 0.10 (Saaty, 2008). This value demonstrates that the expert responses and weightings between criteria, including the Environmental, Social, and Digital dimensions, are stable and logically consistent.
c. Predictive AI Model Validation
The artificial intelligence (AI) model used in this analysis was validated using 10-fold cross-validation. The test results showed a standard deviation of accuracy of 2.1%, indicating high stability and a very low risk of overfitting. This model was proven capable of predicting the Digital Carrying Capacity Index (DCCI) with nearly identical performance consistency across folds. This approach follows the validation standards adopted in machine learning for sustainability research.
d. Field Triangulation and Qualitative Validation
e. To ensure the model's suitability to empirical conditions, field triangulation was conducted with Bromo Tengger Semeru National Park management and local communities. Triangulation results for the July–August 2024 period demonstrated a high correlation between DCCI predictions and actual conditions. During the peak visitation period in August, the model successfully detected a 31% increase in ecotourism pressure, as recorded by management. This strengthens the model's external validity and demonstrates that the integration of System Dynamics Models, Fuzzy Logistics, and AI accurately represents the managerial reality of the destination.

DISCUSSION

The results of this study indicate that the implementation of the Digital Carrying Capacity Management (DCCM) system can reduce tourism pressure by up to 35% and increase ecological carrying capacity efficiency by 28% compared to a conventional (business-as-usual) scenario. These findings confirm that digital transformation is not merely a monitoring tool, but rather a strategic instrument in the adaptive governance of tourism destinations. Within the framework of Dynamic Capability Theory (Teece et al., 1997), a destination's digital capabilities function as a mechanism for 1) Sensing, which recognizes tourism pressure and ecological degradation through IoT sensors; 2) Seizing, which allocates visitor quotas based on predicted environmental loads; and 3) Reconfiguring, which adaptively adjusts quota policies through AI-driven feedback loops. This demonstrates that digital-based destination governance has the dynamic capacity to adapt to fluctuations in tourism and environmental pressures, in line with the concept of Adaptive Systems in Tourism Governance (Hartman, 2021). This model is not only reactive to overtourism but also proactive in maintaining a balance between economic needs and ecological carrying capacity limits.

This finding also aligns with the basic principles of Resilience Theory proposed by Holling (1973), where an ecological system is said to be resilient if it is able to absorb disturbances and maintain its basic functions without experiencing structural collapse. In the context of Bromo Tengger Semeru National Park, the Digital Carrying Capacity Index (DCCI) system functions as a digital early warning system that detects drastic changes in tourist flows, adjusts quota capacity in real time, and maintains long-term ecological equilibrium. Digital Carrying Capacity Management extends the concept of resilience into the realm of digital socio-ecological systems, where feedback loops between IoT data, dynamic models, and predictive AI enable destination systems to remain operational within a “sustainability safe zone” even as tourism pressure increases. This reinforces the view of Biggs et al. (2015) that the application of intelligent technology in nature-based resource management can enhance the ability of social and ecological systems to adapt and thrive in a changing context. In addition, the Digital Carrying Capacity Management model developed in this study also contributes directly to the achievement of various Sustainable Development Goals such as SDG 9 (Industry, Innovation, and Infrastructure) related to the application of digital technology for destination management, SDG 12 (Responsible Consumption and Production) related to the adaptive quota system to regulate tourist intensity, and SDG 13 (Climate Action) related to the mitigation of carbon emissions due to overtourism.

CONCLUSIONS AND RECOMMENDATIONS

This study successfully developed and tested a Digital Carrying Capacity Management (DCCM) model based on the integration of System Dynamics Modeling, Fuzzy-MCDM, and Artificial Intelligence (AI) to control overtourism in Bromo Tengger Semeru National Park, Indonesia. The results showed that the implementation of AI-based Smart Capacity Optimization (SCO) was able to reduce tourism pressure by up to 35% and increase ecological carrying capacity efficiency by 28% compared to the conventional scenario. The digital dimension (IoT sensors, data accuracy, and AI predictions) had the highest contribution weighting in destination sustainability (0.521), surpassing ecological (0.482) and social (0.414) aspects. The DCCI (Digital Carrying Capacity Index) model successfully converted multidimensional data into a comprehensive indicator to monitor the balance between tourism pressure and ecological capacity. Digital integration in destination governance creates an adaptive governance pattern that increases socio-ecological resilience. The results of this study confirm that digital-based carrying capacity management is key to realizing sustainable tourism, especially in nature conservation areas in Indonesia.

The results of this study provide practical guidance for destination managers, governments, and communities in realizing digital-based sustainable tourism. Destination managers are advised to implement an AI-based visitor quota system integrated with the DCCI dashboard to monitor destination capacity in real time. Furthermore, managers are advised to integrate IoT sensors with online ticketing and visitor tracking systems to enable more efficient and adaptive capacity management. For the government, these results recommend the use of DCCI as a decision-making tool within the Sustainable Tourism Management System framework, particularly for application to five national super-priority destinations. Meanwhile, local communities are expected to play an active role in sustainability monitoring through open data ecosystems and develop eco-digital entrepreneurship, a form of digital entrepreneurship oriented towards environmentally friendly and sustainable tourism practices.

ADVANCED RESEARCH

While the findings are promising, several limitations should be acknowledged. First, this study focused on a single case study, Bromo Tengger Semeru National Park, which may limit the generalizability of the proposed Digital Carrying Capacity Management (DCCM) model to other tourism destinations with different ecological, managerial, and socio-cultural characteristics. Future studies should validate the model across national parks and protected areas with diverse tourism patterns. Second, although the integration of System Dynamics Modeling, Fuzzy MCDM, and Artificial Intelligence provides a comprehensive analytical framework, the predictive analysis relies primarily on historical environmental and visitor datasets collected during the 2024 observation period. Consequently, the model has not been evaluated using long-term longitudinal data that could better capture seasonal fluctuations and structural changes in tourism demand.

Third, statistical validation of the machine learning model is limited to conventional performance indicators, including Accuracy, Precision, Recall, ROC-AUC, and 10-fold cross-validation. Future research could strengthen statistical robustness by incorporating external validation datasets, temporal validation, uncertainty analysis, sensitivity analysis, Bayesian inference, or explainable artificial intelligence (XAI) techniques to improve model interpretability and reliability. Finally, future studies should also investigate the causal relationships between digital governance, stakeholder behavior, environmental resilience, and adaptive policy interventions using advanced statistical approaches such as Structural Equation Modeling (SEM), Bayesian Networks, or hybrid simulation models. Such developments would provide stronger empirical evidence regarding the effectiveness and scalability of digital carrying capacity management in sustainable tourism destinations.

REFERENCES

Biggs, R., Schlüter, M., & Schoon, M. L. (2015). An introduction to the resilience approach and principles to sustain ecosystem services in social–ecological systems. Principles for building resilience: Sustaining ecosystem services in social-ecological systems, 1-31.

BPS. (2024). Statistik Pariwisata Indonesia 2024. Jakarta: Badan Pusat Statistik.

Buhalis, D., & Amaranggana, A. (2014, December). Smart tourism destinations enhancing tourism experience through personalisation of services. In Information and communication technologies in tourism 2015: Proceedings of the international conference in Lugano, Switzerland, February 3-6, 2015 (pp. 377-389). Cham: Springer International Publishing.

Cifuentes, M. (1992). Determination of Visitor Carrying Capacity in Protected Areas. World Wildlife Fund, Washington, DC.

Gretzel, U., Sigala, M., Xiang, Z., & Koo, C. (2015). Smart tourism: foundations and developments. Electronic markets, 25(3), 179-188.

Hakim, L., & Nakagoshi, N. (2006, June). Kasodo, tourism, and local people perspectives for Tengger Highland Conservation. In Proceeding of 11th Biennial Conference of International Association for the Study of Common Property IASCP.

Hartman, S. (2021). Adaptive tourism areas in times of change. Annals of Tourism Research, 87, 102987.

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics, 4(1), 1–23.

Jamin, A., & Rahmafitria, F. (2022). Visitor management concept through carrying capacity analysis in forest recreation. Journal of Indonesian Tourism, Hospitality and Recreation, 5(1), 1-12.

Jatim.antaranews.com. (2024). BB-TNBTS gelar aksi bersih sampah di kawasan Bromo tingkatkan edukasi. https://www.antaranews.com/berita/4141938/bb-tnbts-gelar-aksi-bersih-sampah-di-kawasan-bromo-tingkatkan-edukasi.

Lang, X. (2025). Optimizing Art Park Cluster Development In South Korea Through Strategic Resource Management And Innovation. Journal of Modern Project Management, 13(1).

Manning, R. E., Anderson, L. E., & Pettengill, P. (2017). Managing outdoor recreation: Case studies in the national parks. Cabi.

OECD. (2020). The OECD Digital Government Policy Framework. https://www.oecd.org/en/publications/the-oecd-digital-government-policy-framework_f64fed2a-en.html.

O'Reilly, A. M. (1986). Tourism carrying capacity: Concept and issues. Tourism management, 7(4), 254-258.

Patrichi, I. C. (2024). AI solutions for sustainable tourism management: A comprehensive review. Journal of Information Systems & Operations Management, 18(1), 172-185.

Putri, I. A., & Ansari, F. (2021). Managing nature-based tourism in protected karst area based on tourism carrying capacity analysis. Journal of Landscape Ecology (Czech Republic), 14(2), 46-64.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. International journal of services sciences, 1(1), 83-98.

Sadikin, P. N., Arifin, H. S., Pramudya, B. A. M. B. A. N. G., & Mulatsih, S. (2017). Carrying capacity to preserve biodiversity on ecotourism in Mount Rinjani National Park, Indonesia. Biodiversitas, 18(3), 978-989.

Saveriades, A. (2000). Establishing the social tourism carrying capacity for the tourist resorts of the east coast of the Republic of Cyprus. Tourism management, 21(2), 147-156.

Sterman, J. (2002). System Dynamics: systems thinking and modeling for a complex world.

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. Strategic management journal, 18(7), 509-533.

theagilityeffect.com. (2020). Venice plans to use AI to manage crowds. https://www.theagilityeffect.com/en/article/venice-plans-to-use-ai-to-manage-crowds.

UN Tourism. (2025). International tourism recovers pre-pandemic levels in 2024. https://www.untourism.int/news/international-tourism-recovers-pre-pandemic-levels-in-2024.

UNESCO. (2022). World Heritage and Overtourism Report 2022. Paris: UNESCO.

Vetrivel, S. C., Vidhyapriya, P., & Arun, V. P. (2025). AI-Driven Solutions for Crowd Management in Tourism: Navigating the Swarm. In AI Technologies for Personalized and Sustainable Tourism (pp. 83-112). IGI Global.