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Article

Digital Twin Technology-Driven Smart Construction and Application Research of Abandoned Mine Pit Tourism Scenes

Lening Li [1,*]

[1] No.2 Institute of Ecological Landscape Architecture, Shanxi Urban and Rural Planning & Design Institute Co., Ltd., Taiyuan, China

* Correspondence: Lening Li, No.2 Institute of Ecological Landscape Architecture, Shanxi Urban and Rural Planning & Design Institute Co., Ltd., Taiyuan, China

Abstract: Abandoned mine pits, as distinctive post-industrial landscapes, hold considerable potential for tourism development, ecological restoration, and regional regeneration. However, their sustainable utilization is constrained by complex safety risks, environmental degradation, fragmented data, and difficulties in real-time visitor management. This study investigates the application of digital twin technology to construct intelligent, immersive, and interactive tourism scenarios for abandoned mine pits. By integrating multi-source data, including IoT sensor networks, GIS mapping, high-precision 3D modeling, and real-time visitor behavior analysis, a comprehensive digital twin platform is developed to mirror physical conditions and operational states of the site. The platform supports continuous environmental monitoring, structural safety assessment, and dynamic scenario simulation under different visitor flows and climatic conditions. Case studies demonstrate the system's capacity for early risk prediction, emergency response support, and personalized service delivery through adaptive guidance, information visualization, and experience optimization. The research further discusses system architecture, data integration workflows, and key technical challenges related to interoperability and model updating. The findings highlight the transformative potential of digital twins in revitalizing abandoned industrial sites, promoting sustainable tourism, enhancing environmental governance, and supporting smart destination management and planning decisions.

Keywords: digital twin; smart tourism; industrial heritage; environmental monitoring; 3d modeling; visitor management

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1. Introduction

1.1. Research Background and Significance

Abandoned mine pits represent both ecological challenges and cultural heritage resources. As urban expansion and resource depletion continue to intensify, transforming these sites into tourism attractions has emerged as a viable strategy for promoting local economic revitalization and advancing ecological restoration. These locations, however, often encounter multifaceted safety, environmental, and operational challenges that traditional management methods struggle to address effectively. Digital twin technology, which enables the creation of real-time, dynamic virtual replicas of physical environments, presents innovative solutions for monitoring, managing, and optimizing these delicate tourism landscapes. By integrating advanced data analytics and simulation capabilities, this technology can enhance decision-making processes and ensure sustainable development [1, 2].

1.2. Research Status at Home and Abroad

Internationally, digital twin technology has found extensive applications in areas such as smart city management, industrial monitoring, and the management of tourism destinations. For instance, several projects in countries like Germany and South Korea have leveraged digital twins to enhance cultural heritage preservation and optimize visitor flow management [3]. Within China, pilot applications of digital twin technology have been initiated in urban park management and the reclamation of industrial sites. However, there remains a significant gap in research focusing specifically on the utilization of abandoned mine pits as tourism resources. While existing studies demonstrate the technical feasibility of such applications, they often lack comprehensive frameworks that integrate tourism scenario construction with advanced smart applications, highlighting an area for further exploration and development.

1.3. Research Content and Methods

This study develops a comprehensive digital twin-driven smart platform tailored for the enhancement of abandoned mine pit tourism. By integrating advanced technologies such as GIS, IoT sensor networks, 3D modeling, and visitor behavior analytics, the platform aims to revolutionize the management and experience of such unique tourism sites [4, 5]. The research methodology encompasses the collection of environmental data through sensors and drones, enabling precise spatial-temporal simulations of various tourism scenarios. Additionally, the study incorporates safety and risk assessment modeling to ensure visitor security and employs innovative designs for interactive visitor services. A combination of spatial analysis, system development, case study evaluations, and expert interviews is utilized to rigorously validate the platform's operational effectiveness and its potential to deliver practical benefits.

2. Theoretical Foundations and Digital Twin Framework

2.1. Characteristics of Abandoned Mine Pit Tourism Sites

Abandoned mine pits represent distinctive landscapes characterized by a combination of geological, ecological, and cultural attributes that set them apart from conventional tourism sites. From a geological perspective, these areas often feature striking landforms, including deep, irregular pits, steep inclines, and uneven, unstable terrain. Such features pose inherent safety challenges for visitors and developers, necessitating comprehensive risk assessments and the implementation of robust safety measures to prevent accidents and ensure visitor security. Ecologically, abandoned mine pits frequently transform into critical microhabitats that support rare and specialized flora and fauna, some of which may be endemic or endangered. However, these ecosystems are highly sensitive and susceptible to environmental degradation caused by factors such as pollution, acid mine drainage, and soil erosion. This underscores the importance of prioritizing ecological conservation efforts to maintain biodiversity and ecological balance in these areas. Culturally, abandoned mine pits often hold significant historical and cultural value, reflecting the legacy of mining activities, industrial heritage, and the narratives of local communities. Preserving and interpreting this cultural heritage is essential for creating meaningful and educational tourist experiences, fostering a deeper appreciation for regional history [2, 6]. Consequently, sustainable tourism development in abandoned mine pits must carefully integrate multiple objectives: safeguarding and restoring ecological environments, preserving and communicating cultural heritage, and ensuring that visitor experiences are both safe and engaging. Achieving this balance requires a multidisciplinary approach that harmonizes environmental, cultural, and safety considerations.

2.2. Digital Twin Technology and Smart Tourism

Digital twin technology involves the creation of highly detailed and synchronized virtual representations of physical objects, environments, or systems. These virtual models continuously integrate real-time data from sensors, Internet of Things (IoT) devices, and other sources, enabling real-time monitoring, predictive analysis, and interactive simulation [7, 8]. By providing a dynamic mirror of the physical counterpart throughout its lifecycle, digital twins offer significant potential for advancing smart tourism initiatives. Within the tourism sector, this technology enables immersive and personalized experiences, enhances operational efficiency, and promotes safety and sustainability. For instance, tourism operators can utilize digital twins to design virtual scenarios for visitor navigation, crowd management, and emergency response, thereby mitigating risks in complex or hazardous environments such as abandoned mine pits. Additionally, digital twins support continuous environmental monitoring, enabling the timely detection and mitigation of ecological impacts, which aligns with broader conservation objectives. The technology also facilitates adaptive and scenario-based planning, allowing tourism services to dynamically adjust based on visitor preferences, environmental conditions, or emerging challenges. These capabilities are closely aligned with the principles of smart tourism, which emphasize sustainable resource utilization, interactive visitor engagement, and the delivery of customized services tailored to individual needs and contexts. Consequently, digital twins represent a pivotal tool for transforming traditional tourism into a responsive, data-driven, and environmentally responsible industry, fostering innovation and resilience in an increasingly complex global landscape.

2.3. Framework for Digital Twin-Driven Smart Construction

To operationalize the advantages of digital twin technology in the smart construction and management of abandoned mine pit tourism sites, a comprehensive, modular framework is proposed, encompassing four interconnected layers. The first module, the Data Layer, focuses on acquiring and integrating diverse data sources. This includes high-resolution spatial data obtained through remote sensing and GIS, real-time environmental parameters such as air quality, temperature, and soil moisture collected via IoT sensor networks, as well as visitor-related data like foot traffic patterns and behavioral analytics. This robust data foundation ensures accurate and up-to-date representations of the physical environment. The second module, the Modeling Layer, utilizes the collected data to construct precise 3D reconstructions of the mine pit terrain and associated infrastructures. It also simulates visitor movements, potential hazard scenarios, and environmental processes. Advanced spatial analysis and behavior modeling algorithms drive these simulations, providing predictive insights and enabling scenario testing. The third module, the Application Layer, translates modeling outcomes into practical functionalities. These include safety monitoring systems that detect and alert on terrain instability or visitor crowding, environmental management tools that monitor pollution levels and ecosystem health, and interactive platforms for visitor engagement, such as augmented reality experiences and personalized itinerary recommendations. Lastly, the Interaction Layer facilitates real-time communication and feedback between the system and its users, including tourists, site managers, and emergency responders. This layer enables adaptive service delivery and responsive decision-making. The framework operates as a closed-loop system, supporting continuous refinement of management strategies based on operational data and user input. This ensures resilience and sustainability in the development and ongoing stewardship of abandoned mine pit tourism sites, fostering both environmental preservation and enhanced visitor experiences.

3. Core Technologies and Implementation

3.1. GIS and 3D Modeling for Spatial Reconstruction

Geographic Information Systems (GIS) serve as a cornerstone in the spatial reconstruction and detailed mapping of abandoned mine pit tourism sites. These tools enable the integration and analysis of diverse geospatial datasets, such as topographical maps, vegetation distribution, hydrological features, and existing infrastructure, including trails, viewing platforms, and safety barriers. By synthesizing these datasets, GIS provides a comprehensive and layered understanding of the site's physical and environmental attributes. To enhance this process, advanced remote sensing technologies, including Unmanned Aerial Vehicles (UAVs) equipped with high-resolution cameras and Light Detection and Ranging (LiDAR) sensors, are utilized to capture precise three-dimensional representations of the terrain. UAV photogrammetry delivers high-resolution aerial imagery, while LiDAR technology penetrates vegetation canopies to generate accurate elevation models, capturing intricate surface details, steep gradients, and areas of unstable ground. The integration of these datasets results in the creation of highly accurate 3D digital terrain models (DTMs) and 3D textured mesh models, which replicate the complex morphology of the mine pit landscape with remarkable fidelity. These virtual reconstructions are instrumental in supporting various simulations essential for smart tourism development. For instance, they enable the modeling of visitor movement patterns, the identification of hazardous zones susceptible to landslides or collapses, and the strategic placement of scenic viewpoints to enhance visitor experiences while minimizing ecological disruption. Additionally, these 3D models support the development of immersive virtual reality (VR) experiences, allowing for remote exploration and pre-visit planning, thereby improving accessibility and educational opportunities for a broader audience.

3.2. IoT Sensor Networks for Environmental Monitoring

The deployment of distributed Internet of Things (IoT) sensor networks plays a crucial role in the ongoing environmental monitoring of abandoned mine pit tourism sites. These sensor nodes are strategically positioned across key areas to measure a wide array of environmental parameters critical for ecological preservation and ensuring visitor safety. Among the primary variables monitored are air quality indicators, including particulate matter, sulfur dioxide, and nitrogen oxides, which help assess pollution levels and potential health risks. Soil moisture and stability sensors are utilized to evaluate erosion risks and detect potential ground subsidence, while water level gauges monitor fluctuations in groundwater or surface water bodies. Additionally, microclimate instruments measure temperature, humidity, and wind patterns to provide a comprehensive understanding of localized weather conditions. The sensor data are transmitted in real-time to centralized platforms where they are aggregated, processed, and analyzed to identify emerging hazards. These hazards may include landslides caused by soil destabilization, sudden increases in pollutant concentrations due to residual mining contamination, or flash flooding during heavy rainfall events. The IoT system generates early warnings that enable site managers to implement rapid response measures, such as evacuating visitors, temporarily closing affected areas, or initiating targeted environmental remediation efforts. Furthermore, the analysis of long-term environmental data trends supports sustainable site management practices, ensuring a balance between tourism development and ecosystem health.

3.3. Visitor Behavior Analytics and AI Prediction

Understanding visitor behavior is a critical component in optimizing the management and service delivery of abandoned mine pit tourism sites. Modern analytical techniques utilize extensive data sources, including anonymized mobile positioning data, GPS tracking, and social media check-ins, to capture detailed spatiotemporal patterns of visitor distribution, movement paths, dwell times, and points of interest. These datasets

provide valuable insights into visitor interactions with the site, identifying popular attractions, areas prone to congestion, and temporal variations in visitor flows. Advanced artificial intelligence and machine learning algorithms are employed to analyze this complex data, enabling the development of predictive models for visitor behavior. For instance, supervised learning models can estimate visitor volumes based on historical trends, weather conditions, and scheduled events, while clustering algorithms help categorize visitors into distinct groups based on their preferences and behaviors. These AI-driven insights support dynamic route optimization and resource allocation, such as adjusting staffing levels, managing pathway accessibility, and scheduling maintenance during periods of low activity. Furthermore, behavioral analytics enable the creation of personalized recommendations, which can be delivered through mobile applications or digital kiosks to enhance visitor engagement and satisfaction. By integrating predictive analytics with real-time monitoring systems, tourism sites can proactively address crowding issues, minimize environmental impact, and improve operational efficiency. This approach ensures a safer, more sustainable, and enjoyable experience for all visitors.

4. Case Study: Application in Tonglu Abandoned Iron Mine

4.1. Digital Twin Construction Process

At the Tonglu Abandoned Iron Mine, a cutting-edge digital twin platform was developed to facilitate smart tourism initiatives and ensure sustainable management of the site. The construction process commenced with the collection and integration of diverse datasets to create a comprehensive virtual model. High-resolution GIS spatial maps provided detailed insights into the mine pit's topography, vegetation patterns, water bodies, and existing infrastructure, including pathways and safety installations. Additionally, UAV drone flights captured current aerial imagery and generated three-dimensional surface models, while LiDAR scanning contributed highly precise elevation and terrain morphology data, essential for accurately representing the site's complex slopes and uneven surfaces. Environmental data, such as soil moisture levels, air quality metrics, and microclimate conditions, were continuously gathered through a network of IoT sensors strategically deployed in areas vulnerable to erosion or flooding. These data streams were seamlessly integrated into a cloud-based digital twin platform that updates in real-time, ensuring the virtual replica remains dynamic and accurate. This platform enables detailed simulations of visitor movement patterns, identification of high-risk zones, and monitoring of ecosystem health, thereby providing site managers with a robust decision-support tool. Intuitive visualization dashboards enhance understanding of current site conditions, facilitate the issuance of risk alerts, and support coordinated operational responses, ensuring the site's safety and sustainability.

4.2. Smart Scenario Simulation and Risk Management

Building upon the digital twin foundation, the system at Tonglu Abandoned Iron Mine enables advanced scenario simulations designed to predict and mitigate potential risks. The platform models a variety of emergency and environmental scenarios, including intense rainfall that could trigger landslides, the sudden release of pollutants from residual mining deposits, or flash floods that might disrupt visitor pathways. These simulations integrate detailed physical terrain models with visitor behavior predictions generated through AI analytics, enabling management to anticipate crowding issues and identify safety hazards under diverse conditions. For example, evacuation simulations are used to determine optimal egress routes and identify potential bottlenecks, which inform both emergency preparedness plans and real-time response strategies. In cases of adverse weather warnings, the platform dynamically recommends temporary trail closures or alternative visitor routes to minimize exposure to high-risk areas. Additionally, continuous environmental monitoring combined with predictive analytics supports long-term site maintenance and ecological restoration efforts, ensuring that protective measures are implemented in a timely and targeted manner. By delivering actionable

forecasts and tailored intervention strategies, the digital twin system significantly enhances the resilience, safety, and sustainability of the Tonglu Abandoned Iron Mine as a tourism destination, while also promoting effective resource management and environmental stewardship.

4.3. Enhancing Visitor Experience and Services

At Tonglu Abandoned Iron Mine, digital twin technology is utilized not only to ensure safety and environmental management but also to significantly enhance the visitor experience. Interactive mobile applications and on-site digital kiosks provide virtual tours that allow visitors to explore the site's unique terrain, historical mining operations, and natural landscapes both prior to and during their visit. These systems also deliver real-time safety alerts and route guidance, which are tailored to current site conditions, thereby improving visitor awareness and minimizing risks. Augmented reality (AR) features further enrich the interpretive experience by overlaying historical reconstructions of mining equipment, worker lifestyles, and industrial processes onto the physical surroundings. This approach enables visitors to engage more deeply with the site's cultural heritage. Additionally, AR layers emphasize key ecological features and ongoing conservation initiatives, promoting environmental education and awareness. Advanced AI-driven visitor behavior analytics offer personalized recommendations, suggesting optimal trails, rest areas, and points of interest based on individual preferences and mobility levels. By combining immersive digital storytelling, safety guidance, and customized services, the site delivers a more engaging, informative, and accessible tourism experience [9]. This innovative integration of technology supports the sustainable development of the Tonglu Abandoned Iron Mine, positioning it as a leading example of digital twin-enabled smart tourism.

5. Challenges and Future Directions

5.1. Data Integration and Interoperability

The successful development and operation of a digital twin platform for abandoned mine pit tourism depend significantly on the integration of diverse and heterogeneous data sources [10]. These sources often originate from various devices, formats, and systems, encompassing GIS spatial layers, UAV imagery, LiDAR scans, IoT sensor streams, and visitor behavior datasets. Achieving seamless interoperability and efficient data fusion requires the adoption of standardized data formats, communication protocols, and metadata frameworks. Without such standardization, challenges such as data silos and incompatibilities can obstruct real-time synchronization and comprehensive analysis. Additionally, addressing data privacy and security is paramount, particularly due to the inclusion of personal visitor information and continuous environmental monitoring. Establishing robust governance frameworks is essential to define data access rights, implement anonymization procedures, and enforce cybersecurity measures. These frameworks must safeguard sensitive information from unauthorized access or breaches while ensuring transparency and adherence to applicable regulations. Furthermore, fostering collaboration among stakeholders can enhance the development of unified standards and promote innovation in data management practices.

5.2. Technology Adoption and Capacity Building

Despite the significant benefits offered by digital twin technology, its widespread adoption faces considerable challenges related to high initial investment costs, complex technical requirements, and ongoing maintenance demands. Many tourism sites, particularly those situated in remote or economically constrained regions, often lack the financial resources and technical expertise required for effective deployment. Addressing these barriers necessitates capacity building through targeted training programs designed for local site managers, technicians, and decision-makers. Such initiatives are essential for equipping stakeholders with the skills needed to operate and interpret digital twin

systems proficiently. Furthermore, sustainable funding models must be developed to ensure long-term viability. These models could integrate public investment, private partnerships, and reinvestment of tourism-generated revenue to support not only the initial setup but also continuous updates, sensor maintenance, and platform enhancements. Promoting collaboration among technology providers, academic institutions, and local authorities can further facilitate knowledge exchange and innovation, ultimately enabling smoother and more inclusive technology adoption across diverse regions.

5.3. Balancing Conservation and Tourism

A core challenge in developing smart tourism at abandoned mine pit sites lies in achieving a harmonious balance between ecological conservation and the delivery of engaging, educational, and safe visitor experiences [11, 12]. These sites often feature fragile ecosystems and geological instabilities, necessitating adaptive management strategies capable of responding to evolving environmental conditions and visitor behaviors. Digital twin platforms play a pivotal role by enabling continuous environmental monitoring, scenario simulations, and impact forecasting. These tools provide critical insights that inform evidence-based decision-making, allowing managers to dynamically adjust access routes, visitor capacities, and restoration activities based on real-time data. This approach minimizes ecological disturbances while optimizing the benefits of tourism. Additionally, the integration of interpretive technologies, such as augmented reality and personalized visitor guidance systems, enhances tourists' understanding and fosters responsible behavior, thereby reinforcing conservation goals. Achieving this delicate balance requires an iterative management approach that incorporates stakeholder engagement and ongoing evaluation. Such a strategy ensures the long-term sustainability of both the natural environment and the tourism initiatives developed around these unique sites.

6. Conclusion

Digital twin technology offers a groundbreaking approach to transforming abandoned mine pit tourism by facilitating intelligent, adaptive, and participatory management strategies. This study highlights its capacity to significantly improve safety measures, promote environmental sustainability, and enhance visitor experiences, thereby contributing to the sustainable redevelopment of post-industrial landscapes. The broader implications of this technology extend to fostering innovative solutions for complex environmental challenges. Future research should prioritize refining data integration techniques, exploring scalable applications across multiple sites, and fostering deeper engagement with local communities to ensure inclusive and impactful outcomes.

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