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Sustainable Development of Digital Cultural Heritage: A Hybrid Analysis of Crowdsourcing Projects Using fsQCA and System Dynamics

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Abstract: Cultural heritage crowdsourcing has emerged as a promising approach to address the challenges of digitizing and preserving cultural heritage, contributing to the sustainable development goals of cultural preservation and digital inclusivity. However, the long-term sustainability of these projects faces numerous obstacles. This study explores the key configurational determinants and dynamic evolutionary mechanisms driving the sustainable development of cultural heritage crowdsourcing projects, aiming to enhance their longevity and impact. An innovative integration of fuzzy-set qualitative comparative analysis (fsQCA) and system dynamics (SD) is employed, drawing upon a "resource coordination–stakeholder interaction–value co-creation" analytical framework. Through a multi-case comparison of 18 cultural heritage crowdsourcing projects, we identify necessary conditions for project sustainability, including platform support, data resources, knowledge capital, and digitalization performance. The study reveals multiple sufficient pathways to sustainability through configurational combinations of participant motivation, innovation drive, social capital, and social impact. Our system dynamics analysis demonstrates that crowdsourcing project sustainability exhibits significant nonlinear dynamic characteristics, influenced by the interaction and emergent effects of the resource–participation–performance chain. This research offers both theoretical insights and practical guidance for optimizing crowdsourcing mechanisms and sustainable project operations, contributing to the broader goals of sustainable cultural heritage preservation and digital humanities development. The findings provide a roadmap for policymakers and project managers to design and implement more sustainable and impactful cultural heritage crowdsourcing initiatives, aligning with global sustainability objectives in the digital age.

Keywords: sustainable cultural heritage; digital preservation; crowdsourcing sustainability; fuzzy-set qualitative comparative analysis; system dynamics; digital humanities; sustainable development goals

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1. Introduction

The emergence of digital humanities and the evolution of cultural heritage preservation concepts have given rise to cultural heritage crowdsourcing as a collaborative model that promotes public participation and harnesses collective wisdom. This approach offers new solutions to address the resource, technological, and human capital bottlenecks faced in the digitization of cultural heritage [1]. Enabled by digital platforms and Web 2.0 technologies, cultural heritage crowdsourcing has been widely applied in the digitization efforts of museums, libraries, and archives. These applications include tasks such as artifact annotation, literature indexing, and historical document collation, injecting new momentum into the digital acquisition, processing, display, and dissemination of cultural heritage resources.

From globally renowned Zooniverse projects in humanities and history to large-scale humanities volunteer initiatives launched by the European Digital Library, the U.S. Library of Congress, and the UK National Archives, as well as domestic projects like "Digital Gazetteers" and "Family Tree Digitization" undertaken by major cultural institutions in China, cultural heritage crowdsourcing practices have continuously deepened. These practices have fostered a new ecosystem characterized by institutional leadership, social participation, open collaboration, and contribution-oriented approaches [2].

However, as cultural heritage crowdsourcing practices have been implemented and advanced, issues of sustainable development have become increasingly prominent [3]. Related studies indicate that the long-term financial support required for project operation, incentive mechanisms for sustained volunteer participation, and open access and reuse of project outcomes all pose challenges to the sustainable development of crowdsourcing projects [4]. Lascarides and Vershbow (2014), in their examination of the New York Public Library's "What's on the Menu?" project, found that the initial surge of social attention and participatory enthusiasm did not effectively translate into sustained momentum, with volunteer contributions gradually declining over time [5]. Similarly, the "Ancient Lives" project conducted by the University of Oxford on the Wikipedia platform faced difficulties such as participant attrition and fragmentation of contributions, raising concerns about project sustainability [6]. Furthermore, numerous studies have shown that the long-term performance of cultural heritage crowdsourcing projects is influenced by the interactive effects of various factors, including platform design, participation thresholds, task granularity, community atmosphere, and reputation incentives [7–9], exhibiting significant non-linear characteristics and dynamic complexity. Therefore, promoting the sustainable development of cultural heritage crowdsourcing projects requires not only resource guarantees but also optimization of crowdsourcing mechanisms, mobilization of diverse participatory motivations, and cultivation of an open, collaborative, and innovative crowdsourcing ecosystem.

Existing research on the sustainability of cultural heritage crowdsourcing has predominantly focused on singular aspects such as participation motivation [10], task design [11], and user experience [12], with few studies exploring the impact mechanisms of project sustainability from a holistic perspective. While some scholars have proposed multidimensional sustainable development frameworks encompassing institutional, technological, organizational, and cultural aspects [13], these primarily emphasize theoretical exposition and lack empirical exploration. Additionally, existing research has paid insufficient attention to cultural heritage crowdsourcing as a complex system involving multiple actors, cross-contextual interactions, and dynamic evolution, exhibiting characteristics such as "non-homogeneity", "emergence", and "adaptivity" [14]. Given that the sustainability of digital humanities projects depends not only on the combination of key elements but also on the complex interactions of these elements in dynamic processes [15], clarifying the key configurations driving the sustained success of cultural heritage crowdsourcing projects and their cross-contextual differences, as well as examining the dynamic evolutionary patterns of crowdsourcing systems under different scenarios, is crucial for understanding and addressing the sustainability challenges of cultural heritage crowdsourcing.

Based on the above analysis, this study poses the following research questions:

① What are the key factors constituting the core conditions influencing the sustainable development of cultural heritage crowdsourcing projects? How do these factors form differentiated pathways driving project sustainability through various combinatorial configurations?

② As a complex system, what dynamic evolutionary characteristics does the sustainable development of cultural heritage crowdsourcing projects exhibit? How do the interactive effects and emergent properties of elements within the resource–participation–performance chain shape the long-term viability of projects?

③ What theoretical explanatory power does the "Resource Synergy–Stakeholder Interaction–Value Co-creation" analytical framework possess in interpreting the sustainable development mechanisms of cultural heritage crowdsourcing projects? By integrating fuzzy-set qualitative comparative analysis (fsQCA) and system dynamics (SD) methods, how can the intrinsic generative logic underlying crowdsourcing project success or failure be revealed from both static configurational and dynamic evolutionary dimensions?

In order to resolve these questions, the present study, based on an analytical framework of "resource synergy–subject interaction–value co-creation," innovatively combines fuzzy-set Qualitative Comparative Analysis (fsQCA) and System Dynamics (SD) methods. This approach aims to provide an in-depth analysis of the sustainable development mechanisms of cultural heritage crowdsourcing projects from both configurational and dynamic perspectives. The study first conducts a comparative analysis of 18 representative cultural heritage crowdsourcing project cases, examining how combinations of elements from resource, subject, and value dimensions shape the heterogeneity of project sustainability performance, and exploring the "sufficient conditions" for achieving sustainable project development, i.e., diverse pathways to high performance. Building on this, the study further constructs a system dynamics model reflecting the key feedback structures of cultural heritage crowdsourcing projects. Through computer simulations, it examines the dynamic evolutionary behavior of crowdsourcing systems under different initial conditions, external scenarios, and internal mechanisms, revealing the leverage variables driving project sustainability and their mechanisms of action. The combination of fsQCA and SD is expected to achieve a unification of multi-case comparative analysis and dynamic complexity modeling, laying the foundation for a comprehensive understanding of the generative logic of sustainable development in cultural heritage crowdsourcing projects.

The theoretical significance of this research lies in the following: First, based on the analytical framework of "resource synergy–subject interaction–value co-creation", it comprehensively considers the shaping effects of factors at the resource, subject, and value levels on project sustainability, expanding beyond previous research perspectives focused on single dimensions and providing a more systematic and holistic theoretical perspective for examining the sustainable development of cultural heritage crowdsourcing projects. Second, the innovative application of fsQCA to explore configurational patterns of sustainable development in a multi-case comparative context helps reveal the non-homogeneous and complex characteristics of the success and failure of cultural heritage crowdsourcing projects, enriching theoretical understanding of their impact mechanisms. Third, the introduction of methods such as feedback structure analysis and numerical simulation from system dynamics provides new tools for dynamically examining the interactive effects and emergent behaviors of the resource–participation–performance chain, deepening theoretical understanding of cultural heritage crowdsourcing projects as complex adaptive systems.

In practical terms, by revealing the key configurations driving the sustained success of cultural heritage crowdsourcing projects and their dynamic evolutionary patterns, this research can provide a scientific basis for optimizing crowdsourcing mechanism design, balancing diverse stakeholder interests, and fostering an open collaborative ecosystem. In particular, the differences in typical case configurations identified through fsQCA can offer path references for cultural heritage crowdsourcing practices in different contexts; the leverage elements and regulatory strategies revealed through SD simulations can provide handles for dynamic project governance and addressing uncertainties and risks. Furthermore, by focusing on cultural heritage crowdsourcing in the context of digital humanities, this study has certain inspirational significance for expanding the research horizon of crowdsourcing in the humanities and social sciences and enriching the application of complexity science in the field of cultural heritage.

The structure of this paper is as follows: Section 1 introduces the research background and design; Section 2 proposes a theoretical framework of "resource synergy–subject interaction–value co-creation" based on a review of relevant literature and discusses the combined application of fsQCA and SD; Section 3 employs fsQCA to conduct a multi-case comparative analysis, exploring the shaping effects of resource, participation, and value dimension condition configurations on project sustainability, and constructs and simulates a system dynamics model of crowdsourcing projects to examine the dynamic interactive effects of key elements; Section 4 comprehensively discusses the main conclusions and theoretical contributions of the sustainable development of cultural heritage crowdsourcing projects as reflected in the fsQCA and SD simulation results; and Section 5 summarizes the research findings and practical implications.

2. Problem Description and Research Framework

2.1. Defining Digital Humanities Cultural Heritage Crowdsourcing Projects and Their Sustainability Implications

The widespread application of digital technologies and the digital turn in humanities and social sciences have gradually established digital humanities as a new paradigm for the protection, inheritance, and research of cultural heritage [16]. As a bridge connecting computational methods with humanistic interpretation, digital humanities employ digital technological means to conduct digitization, semanticization, and intelligent processing of cultural heritage. Simultaneously, it emphasizes value interpretation, critical reflection, and subject participation from a humanistic perspective [17]. Within the digital humanities paradigm, the protection and transmission of cultural heritage are no longer the sole responsibility of a single institution but rather an open practice involving the collaborative participation of diverse stakeholders.

Cultural heritage crowdsourcing represents a significant manifestation of the digital humanities paradigm in the heritage domain. It refers to a collaborative model that harnesses public wisdom through digital platforms, inviting the general public to participate in tasks such as the digitization, transcription, proofreading, and research of cultural heritage [18]. Unlike traditional expert-led models, cultural heritage crowdsourcing emphasizes leveraging the power of diverse actors, introducing non-professional groups such as the general public and volunteers to participate in the digital production of cultural heritage, thus achieving open collaboration between institutions and the public. From the perspective of participating subjects, it includes not only professional forces such as cultural institutions, universities, and research institutes but also numerous amateur enthusiasts with knowledge, skills, and passion for cultural heritage. In terms of participation methods, the public can engage in various digital tasks through online platforms, such as artifact annotation, ancient text transcription, local chronicle proofreading, and audio-video translation, as well as participate in knowledge discussions, value interpretations, and re-creations behind the heritage [19]. By gathering collective wisdom and strength, the cultural heritage crowdsourcing model effectively compensates for the shortage of professional resources, enhances the productivity of digital humanities projects, and accelerates the digitization process of cultural heritage.

However, the development of cultural heritage crowdsourcing projects is not achieved overnight. Related studies have pointed out that the operation of crowdsourcing projects not only faces numerous challenges such as resource allocation, incentive mechanisms, and task design [20], but also increasingly highlights long-term sustainability issues [21]. The concept of sustainability, originally derived from the field of ecological environment, emphasizes meeting the needs of the present generation while maintaining the ability of future generations to meet their own needs [22]. In the context of digital humanities, the connotation of sustainability has been expanded, focusing not only on the continuous operation of projects but also on the ongoing acquisition, sharing, utilization, and preservation of data/content [23]. For cultural heritage crowdsourcing projects, sustainable development implies extending the project lifecycle in terms of resources, participation, and performance, providing continuous impetus for the digitization and dynamic inheritance of cultural heritage resources. Specifically, the connotation of sustainable development for cultural heritage crowdsourcing projects can be understood from the following dimensions:

(1) Resource Sustainability: This entails stable and sufficient resource input, including the continuous supply of key resources such as funding, technology, equipment, and talent, providing solid support for project operations [24]. It also includes

shared and open data resources and digital content, serving as "raw materials" for knowledge production.

(2) Participation Sustainability: This involves continuously attracting and maintaining broad participation from diverse actors, achieving growth in the scale of participating groups, and optimizing their structure, while maintaining community activity and contribution levels [25].

(3) Collaboration Sustainability: This refers to establishing an open, trusting, and mutually beneficial collaborative network, achieving ongoing synergy among multiple actors in terms of goals, actions, and interests [26], forming a positive ecosystem of mutual support and complementary progress.

(4) Innovation Sustainability: This involves continuously generating digital outcomes and innovative contributions, achieving ongoing breakthroughs in knowledge discovery, methodological innovation, and application expansion [27], and injecting new momentum into cultural heritage research and digital humanities development.

(5) Impact Sustainability: This entails achieving widespread dissemination and in-depth application of project outputs, continuously exerting influence in areas such as cultural inheritance, academic research, social education, and creative industries [28], driving the sustainable development of cultural heritage endeavors.

2.2. "Resource Synergy–Subject Interaction–Value Co-Creation" Analytical Framework

Cultural heritage crowdsourcing projects, as complex socio-technical systems (STSs), are influenced by interacting factors from various levels, including resource, interpersonal, and organizational layers [29]. To systematically examine the multidimensional influence mechanisms driving the sustainable development of cultural heritage crowdsourcing projects, this study constructs an analytical framework of "Resource Synergy–Subject Interaction–Value Co-creation" based on the following theoretical perspectives (as shown in Figure 1, which is an original creation by the authors based on a synthesis of relevant literature):

Figure 1 presents a visual representation of the "Resource Synergy–Subject Interaction–Value Co-creation" framework, illustrating the interconnections among its key components and their hypothesized influence on project sustainability. The proposed framework serves as a comprehensive methodological guide for investigating the complex dynamics of cultural heritage crowdsourcing sustainability. It integrates key concepts and propositions from resource-based theory, stakeholder theory, and value co-creation theory to capture the multi-layered, interactive nature of crowdsourcing systems. Specifically, the "Resource Synergy" dimension emphasizes the critical role of resource orchestration in driving project performance, including the acquisition, integration, and deployment of technological, informational, and social resources. The "Subject Interaction" dimension highlights the dynamic interplay among diverse stakeholders (e.g., project organizers, participants, and partner institutions) in shaping crowdsourcing outcomes, considering factors such as motivation alignment, governance mechanisms, and collaborative networks. The "Value Co-creation" dimension stresses the participatory, iterative process through which multiple actors jointly generate and realize value in crowdsourcing projects, encompassing both tangible outputs (e.g., digitized cultural heritage artifacts) and intangible benefits (e.g., knowledge sharing, community building).

(1) Resource-Based View (RBV) Perspective: RBV theory posits that an organization's sustainable competitive advantage stems from its unique, scarce, and irreplaceable resource endowments [30]. Applying RBV to the context of cultural heritage crowdsourcing implies that project sustainability must be based on the continuous acquisition and optimal allocation of key resources. On one hand, the digital platform, as the core carrier connecting crowdsourcing tasks and participants, largely determines the efficiency and innovativeness of project implementation through its functionality, usability, and interactivity [31]. Therefore, continuously optimizing platform infrastructure and improving mechanisms for task publishing, review, and interaction is crucial technical support for driving project

sustainability. On the other hand, rich, high-quality cultural heritage data resources are core elements for attracting participants and supporting value creation. The crowdsourcing process relies on massive digital cultural heritage resources, continuously expanding the semantic information and application scenarios of these resources through participants' descriptions, annotations, associations, and reuse, providing "fuel" for cultural heritage and digital humanities research. Simultaneously, crowdsourcing projects heavily depend on participants' knowledge capital (e.g., cultural heritage knowledge, digital skills) and the social capital accumulated by the platform (e.g., trust relationships, reciprocity norms). Continuously optimizing mechanisms for cultivating knowledge capital and converting social capital injects sustained momentum into the project [32].

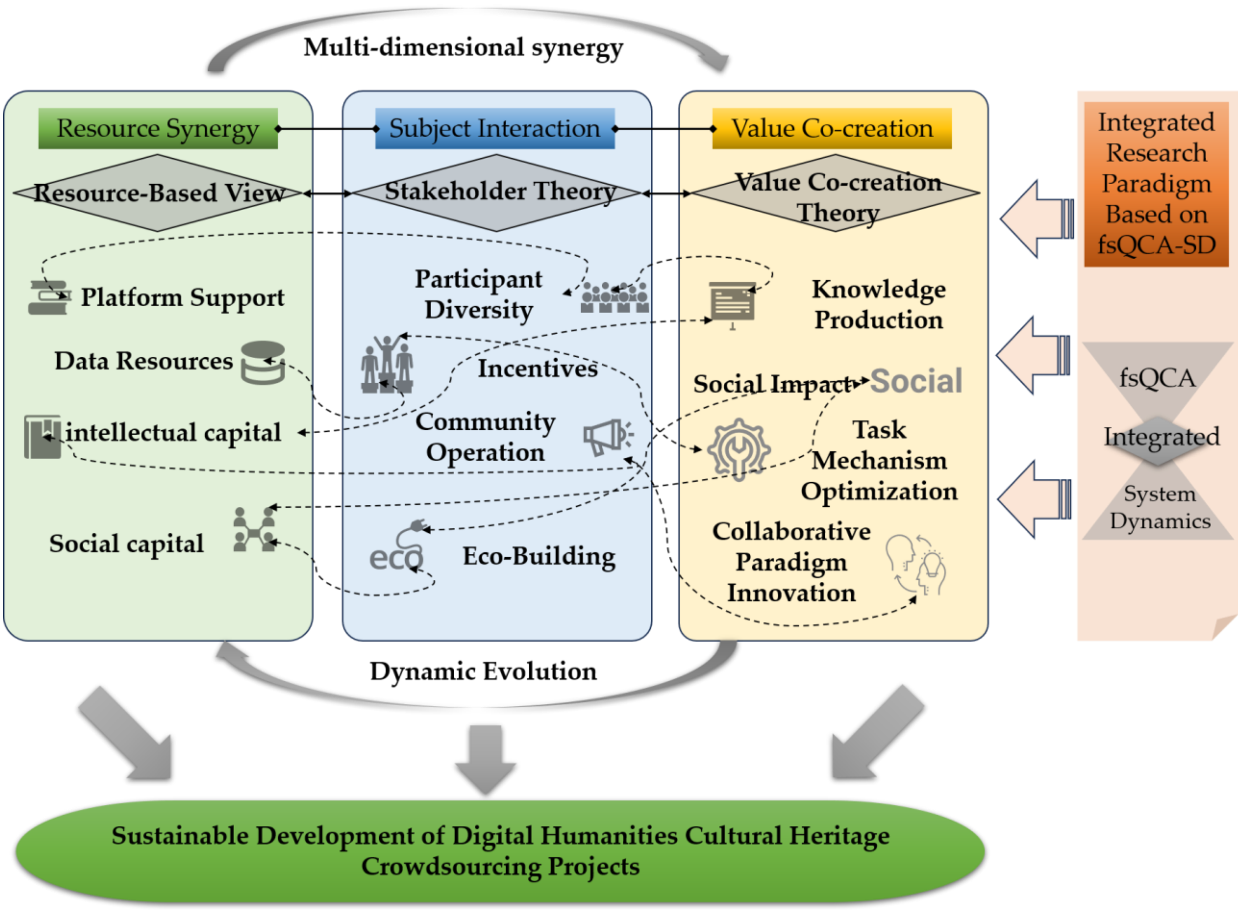

Figure 1. "Resource Synergy–Subject Interaction–Value Co-creation" analytical framework. (Source: Author's original creation based on literature synthesis).

(2) Stakeholder Theory Perspective: Stakeholder theory emphasizes that organizations should balance the interests of different stakeholders. By coordinating relationships with internal and external stakeholders, organizations can achieve dynamic equilibrium with their environment and promote sustainable development [33]. Applying this theory to cultural heritage crowdsourcing requires focusing on how the diversity of participating subjects and the dynamic evolution of their interactive relationships affect project sustainability. On one hand, cultural heritage crowdsourcing projects connect professional institutions such as museums, libraries, archives, and research institutions with numerous non-professional groups possessing cultural heritage knowledge, skills, and enthusiasm. The motivations, behavioral patterns, and interaction modes of these diverse stakeholders profoundly influence the project's development trajectory. It is necessary to employ incentive mechanisms, reputation systems, and emotional design to fully mobilize the enthusiasm of different types of subjects, achieving large-scale mobilization and sustained

contributions [34]. On the other hand, the construction of a cultural heritage crowdsourcing ecosystem is inseparable from the formation and strengthening of trust, reciprocity, and collaborative relationships among participating subjects. Attention should be paid to building a supportive community environment, fostering an open, equal, and sharing participatory culture, strengthening horizontal connections among participants, and promoting the emergence of collective wisdom [35].

(3) Value Co-creation Theory Perspective: Value co-creation theory suggests that value is not created unilaterally but dynamically generated through stakeholder interaction, dialogue, and participation [36]. In the digital humanities era, the value of cultural heritage increasingly exhibits multidimensional and generative characteristics, its creation relying on the collaborative interaction of cross-boundary subject networks [37]. Introducing value co-creation theory to analyze cultural heritage crowdsourcing implies that crowdsourcing value is not preset and unidimensional but embedded in the dynamic process of continuous interaction and collective construction by multiple subjects. In terms of direct crowdsourcing outputs, innovative task design, optimized workflows, and mobilization of community collective wisdom can sustainably enhance the breadth, depth, and precision of cultural heritage digitization. Regarding the spillover effects of crowdsourcing, the collision of perspectives and cross-boundary collaboration brought by diverse subjects can sustainably catalyze new questions, methods, and perspectives in cultural heritage research, injecting vitality into digital humanities knowledge production [38]. More importantly, closely integrating crowdsourcing practices with the realization of the social value of cultural heritage, through open sharing and wide application of results, enhances public awareness of cultural heritage and drives the development of cultural and creative industries, contributing to a virtuous cycle of cultural heritage protection, dissemination, and reuse.

Integrating these theoretical perspectives, this paper constructs an analytical framework of "Resource Synergy–Subject Interaction–Value Co-creation," depicting the internal mechanisms influencing the sustainable development of cultural heritage crowdsourcing projects from the dimensions of resource, interpersonal, and organizational layers. This framework reveals that the fundamental driver of sustainable development in crowdsourcing projects lies in achieving continuous optimization of key resource allocation, deep collaborative interaction among diverse subjects, and dynamic creation and transmission of multidimensional value. Specifically:

In resource synergy, the focus is on continuous optimization of platform facilities, sustained supply of cultural heritage resources, and ongoing accumulation of knowledge and social capital, solidifying the foundation for project development.

In subject interaction, the emphasis is on participant diversity and synergy, prioritizing participation incentives, community operations, and ecosystem building to mobilize and regulate the participatory behavior of diverse subjects.

In value co-creation, attention is given to multiple value dimensions such as knowledge production and social impact, optimizing task mechanisms and collaborative paradigms to enhance the innovative performance of collective wisdom.

These three levels mutually support and dynamically evolve, shaping the endogenous driving force for the sustainable development of cultural heritage crowdsourcing projects.

2.3. Integrated Research Paradigm Based on fsQCA-SD

To thoroughly investigate the influence mechanisms of sustainable development in cultural heritage crowdsourcing projects, this paper adopts an integrated research paradigm combining Fuzzy-Set Qualitative Comparative Analysis (fsQCA) and System Dynamics (SD). The fusion of fsQCA and SD methods helps identify key condition configurations driving project sustainability from a static, combinatorial perspective while simulating the interactive pathways of condition elements from a dynamic, evolutionary viewpoint. This approach examines the diversity and non-homogeneity characteristics of crowdsourcing project evolution while considering its dynamics, adaptability, and emergence as a complex system, thus forming a more comprehensive and in-depth understanding of the generative mechanisms of project sustainability.

fsQCA, originating from Qualitative Comparative Analysis (QCA), was proposed by Ragin (2000) to achieve case-oriented causal complexity analysis through Boolean algebra [39]. Unlike traditional statistical methods focusing on the "net effects" of independent variables, fsQCA employs Boolean algebra to formalize the causal relationships of cases, exploring how combinations of multiple condition variables produce results through truth table construction. It is suitable for revealing complex causal mechanisms in multi-case comparative studies [40]. In recent years, fsQCA has been widely applied in fields such as organizational management and information systems [41], offering unique advantages in testing necessary and sufficient conditions, simplifying causal complexity, and exploring multiple equifinal causal pathways. Introducing fsQCA to analyze the sustainable development of cultural heritage crowdsourcing projects helps examine the combinatorial effects of factors from different levels such as resources, participation, and innovation, revealing key configurations driving project success. Moreover, systematic comparison across cases helps discover the "sufficient conditions" for achieving project sustainability, i.e., multiple sufficient pathways to high performance, deepening the understanding of the mechanisms behind crowdsourcing project success and failure.

The key mathematical steps involved in fsQCA are as follows:

① Calibration of fuzzy-set membership scores: The first step is to transform the original data into fuzzy-set membership scores ranging from 0 to 1, representing the degree of membership in a given set. The calibration process involves setting three qualitative anchors: full membership (1), crossover point (0.5), and full non-membership (0). The fuzzy-set membership score of a case i in set X is calculated using the following logistic function:

$$\mu_X(i) = \frac{1}{1 + e^{-(\frac{x_i - \beta}{\alpha})}}$$

where x_i is the original score of case i, β is the crossover point, and α is the bandwidth parameter determining the slope of the logistic curve.

② Construction of the truth table: Once the fuzzy-set membership scores are calibrated, a truth table is constructed listing all possible combinations of condition variables (2^k, where k is the number of conditions). Each row of the truth table represents a specific configuration of conditions, and the corresponding consistency and frequency scores are calculated. Consistency measures the degree to which cases sharing a given condition or combination of conditions agree in displaying the outcome, calculated as:

$$Consistency(X \leq Y) = \frac{\sum_{i=1}^{n} \min(X_i, Y_i)}{\sum_{i=1}^{n} X_i}$$

where X_i is the membership score of case i in the set of condition X, and Y_i is its membership score in the outcome set Y.

③ Analysis of necessary conditions: A condition is considered necessary if its consistency score exceeds a pre-specified threshold (usually 0.9). The necessity of individual conditions is tested using the formula:

$$Necessity(X \leftarrow Y) = \frac{\sum_{i=1}^{n} \min(X_i, Y_i)}{\sum_{i=1}^{n} Y_i}$$

④ Analysis of sufficient conditions: Sufficiency analysis identifies combinations of conditions that consistently lead to the outcome. The truth table rows are first filtered based on frequency and consistency thresholds, and then logically minimized using Boolean algebra to derive solution formulas. The coverage score measures the empirical relevance of a solution, calculated as:

$$Coverage(X \rightarrow Y) = \frac{\sum_{i=1}^{n} \min(X_i, Y_i)}{\sum_{i=1}^{n} Y_i}$$

Three types of solution formulas are generated: complex, parsimonious, and intermediate, representing different levels of simplification based on the treatment of logical remainders (rows without empirical cases).

⑤ Evaluation of solution consistency and coverage: The overall consistency and coverage of the solution formulas are assessed to determine their empirical significance. High consistency and coverage scores indicate that the identified configurations are sufficient conditions for the outcome and account for a substantial proportion of empirical cases.

System Dynamics is a modeling and simulation method for analyzing complex system behavior by constructing computer simulation models of feedback systems [42]. This method focuses on how system structure, feedback processes, and time delays affect system behavior, describing dynamic associations between system variables through tools such as Causal Loop Diagrams and Stock and Flow Diagrams. It uses computer simulation experiments to analyze system evolutionary behavior under different scenarios and is widely applied in complexity research in fields such as ecology, economics, and management [43]. The "holistic thinking" concept and the basic assumption that "structure determines behavior" in System Dynamics provide powerful tools for examining the dynamic complexity of cultural heritage crowdsourcing projects. By characterizing the causal feedback relationships among elements from different dimensions such as resource, subject, and value layers, and simulating system evolution trajectories under different initial conditions and parameter settings in computers, it helps to deeply understand the nonlinear dynamic characteristics of crowdsourcing projects, predict project sustainability trends under different scenarios, and provide decision-making references for project optimization.

fsQCA and SD methods reflect static comparative and dynamic modeling approaches, respectively, and their combined application can achieve complementary advantages. On one hand, the key influential factor configurations revealed by fsQCA can provide a theoretical basis for SD model development, helping define model boundaries, determine key variables, simplify causal structures, and enhance the theoretical relevance of SD models. On the other hand, fsQCA's emphasis on case heterogeneity can inspire multi-scenario design in SD models, enhancing the case-specific explanatory power of models by simulating how specific conditions in different cases produce differentiated performance. Conversely, SD modeling can compensate for the static limitations of fsQCA by placing element configurations revealed by QCA into the time dimension, observing their dynamic evolution processes through simulation experiments, and testing the robustness of necessary and sufficient conditions over time scales. SD can also examine dynamic characteristics such as feedback delay effects and critical point behaviors that are difficult for QCA to reveal through sensitivity analysis and other means. Therefore, the integrated application of fsQCA and SD can, to some extent, achieve a "win-win" situation between case-oriented research based on Boolean logic and holistic modeling based on feedback thinking [44].

Guided by this, the present study adopts a technical route of "theory construction–comparative analysis–simulation modeling–scenario simulation–theory refinement," comprehensively applying fsQCA and SD methods to explore the influence mechanisms of sustainable development in cultural heritage crowdsourcing projects. Specific steps include the following:

Step 1. Constructing a theoretical analysis framework of "Resource Synergy–Subject Interaction–Value Co-creation" based on literature review, establishing the theoretical foundation for fsQCA and SD models;

Step 2. Based on the theoretical framework and combined with case materials, using fsQCA to explore key influential factor configurations under different pathways, with typical condition variable combinations from resource, subject, and value layers as independent variables and project sustainability assessment as the dependent variable;

Step 3. Referring to fsQCA results and combining them with the theoretical framework, constructing SD Causal Loop Diagrams and Stock and Flow Diagrams reflecting the dynamic complexity of cultural heritage crowdsourcing projects;

Step 4. Estimating model parameters, developing SD simulation models, simulating dynamic changes in system variables under different scenarios, and analyzing key driving factors and leverage points promoting project sustainable development;

Step 5. Integrating fsQCA and SD simulation results to refine the theoretical mechanisms of project sustainable development and propose optimization strategies for cultural heritage crowdsourcing.

3. Research Process and Results

3.1. Configuration Analysis of Digital Humanities Cultural Heritage Crowdsourcing Projects' Sustainable Development Based on fsQCA

3.1.1. Case Selection and Data Collection

Guided by the "Resource Synergy-Subject Interaction-Value Co-creation" theoretical framework, this study employed a combination of purposive sampling and theoretical sampling to obtain a case combination that fully reflects the dimensions of the framework and supports the research objectives.

The research team first extensively collected cultural heritage crowdsourcing projects from around the world. Data sources included renowned crowdsourcing platforms (such as Zooniverse), authoritative institutional crowdsourcing project repositories (like the U.S. Library of Congress), relevant academic conferences, and journals. The collected cases covered multiple types of initiators (museums, libraries, archives, academic institutions), various disciplinary fields (archaeology, history, art, natural sciences), and diverse task types (transcription, annotation, translation, identification).

Based on this broad collection, the research team conducted purposive sampling according to the theoretical framework, focusing on the following dimensions:

(1) Richness of resource synergy, selecting projects with distinctive features in platform support, digital resources, knowledge capital, and social networks (e.g., By the People, MicroPasts);
(2) Diversity of subject interaction, covering different levels of interaction types, such as between crowdsourcing participants and project platforms (Smithsonian Digital Volunteers), among participants (Field Expedition: Mongolia), between participants and audiences (Wikidata), and between platforms and the general public (Europeana 1914–1918);
(3) Typicality of value co-creation, encompassing projects with outstanding achievements in cultural heritage digitization (Yad Vashem), knowledge innovation (Transcribe Bentham), and social impact (Old Weather).

Through purposive sampling, the research team selected 50 candidate cases from the large sample.

Subsequently, the research team conducted an in-depth case evaluation of the candidate cases, focusing on the following:

(1) Whether the project provided detailed process records and rich unstructured data, offering sufficient raw material for analyzing resource input, subject behavior, and value output;
(2) Whether the project demonstrated unique resource synergy mechanisms, subject interaction patterns, or value creation pathways that could provide insightful analytical dimensions for the theoretical framework;
(3) Whether the project had a certain demonstration effect and influence, attracting industry attention and academic research, facilitating data collection and verification [45].

Based on the case evaluation, the research team selected 20 high-quality cases. Finally, as case data were collected and analyzed, the research team found that some cases showed theoretical saturation, with repetitive cases unlikely to provide new insights for the theoretical framework. To pursue theoretical saturation in the case combination [46], the research team optimized the case combination, eliminating 2 cases with high theoretical repetition, ultimately determining 18 cases as research subjects (see Table 1). These cases formed complementarities in theoretical dimensions such as resource synergy, subject interaction, and value co-creation, including both typical samples and extreme cases, capable of supporting the expansion and refinement of the theoretical framework.

Table 1. List of cases of cultural heritage crowdsourcing projects.

No.	Case Name	Initiating Organization	Academic Field	Task Type
1	Ancient Lives	University of Oxford	History	Transcription and Translation of Papyri
2	By the People	Library of Congress	History	Transcription and Tagging of Historical Documents
3	Smithsonian Digital Volunteers	Smithsonian Institution	Multidisciplinary	Enhancing Accessibility of Digital Collections
4	MicroPasts	UK Cultural Heritage Institutions	Archaeology and History	Crowdsourcing Tasks for Archaeology and Historical Documents
5	Zooniverse	International Crowdsourcing Platform	Multidisciplinary	Various Fields Including Humanities and Natural Sciences
6	Old Weather	Zooniverse Project	Meteorology	Transcription of Ship's Logs
7	Europeana 1914–1918	Europeana	History	Collection and Digitization of WWI-Related Items
8	Prokudin-Gorskii	Crowdsourcing Project	Photography	Restoration of Color Photos
9	Transcribe Bentham	University College London	Philosophy	Transcription of Philosopher's Manuscripts
10	What's on the Menu?	New York Public Library	Food Culture	Transcription of Historical Menus
11	Wikidata	Sister Project of Wikipedia	Multidisciplinary	Construction of a Knowledge Graph
12	Papers of the War Department	US War Department Archives Project	History	Transcription and Annotation of War Department Documents
13	Cultural Heritage Imaging	Non-profit Organization	Cultural Heritage	Digitization and Crowdsourcing Projects
14	Yad Vashem	Yad Vashem Memorial	History	Entry and Annotation of Holocaust Victim Information
15	Library of Congress Flickr Commons	Library of Congress	Photo Annotation	Tagging and Commenting on Historical Photos
16	The Great War Archive	University of Oxford	History	Collection and Digitization of WWI-Related Items and Letters
17	Field Expedition: Mongolia	National Geographic and Mongolian Academy of Sciences	Archaeology	Marking Potential Archaeological Sites on Satellite Images
18	Measuring the ANZACs	New Zealand National Archives and University of Waikato	History	Transcription and Annotation of Soldiers' Records

The collection of research data adopted a multi-method approach combining archival research, content analysis, semi-structured interviews, and non-participant observation [47]. Firstly, the research team systematically reviewed project websites, social media accounts (such as Twitter, Facebook), related media reports, secondary literature, blog posts, and academic publications for the selected cases. Using the Internet Archive's Wayback Machine tool, researchers traced the historical evolution process of project websites, examining changes in design, content, and user interactions over time [48]. Secondly, semi-structured interviews were conducted with key informants from each project, including project managers, team members, and active participants. The interviews focused on understanding the project's goals, resources, challenges, strategies, and sustainability practices. A total of 36 interviews were conducted, each lasting 60–90 min. All interviews were transcribed verbatim and coded thematically. Thirdly, non-participant observation was carried out on the project platforms and related online communities. Researchers observed user interactions, engagement patterns, and community dynamics for a period of six months. Field notes were taken to capture key events, behaviors, and emerging themes. The collected data were triangulated to ensure reliability and validity [49]. Two researchers independently conducted an in-depth analysis of the materials and performed open coding based on the theoretical framework. Discrepancies were resolved through discussion and consensus. The research team also regularly consulted with domain experts to confirm the accuracy and consistency of coding results. To maximize the credibility and transferability of findings, the research process followed established case study protocols.

3.1.2. Measurement of Condition Variables and Outcome Variable

Based on the "Resource Synergy–Subject Interaction–Value Co-creation" theoretical framework, this study established seven condition variables and one outcome variable. The seven condition variables measure key factors influencing the sustainable development of cultural heritage crowdsourcing projects from three dimensions: resource synergy, subject interaction, and value co-creation. The outcome variable measures the overall sustainable development level of the project.

(1) Condition Variables in the Resource Synergy Dimension

Platform Support (PLA): examines the support role of crowdsourcing platform characteristics such as technical function completeness, user interface friendliness, and system operation stability for project development, measured using a 5-point Likert scale.

Data Resources (DAT): measures the scale, quality, diversity, and accessibility of digital cultural heritage resources owned and utilized by the project, including the quantity, type, and metadata richness of digitized objects, measured using a 5-point Likert scale.

Knowledge Capital (KNO): assesses the knowledge and skill level of volunteers gathered by the project, the diversity of their professional backgrounds, and the professional accumulation of the project team in the cultural heritage field, measured using a 5-point Likert scale.

Social Capital (SOC): considers the atmosphere of mutual trust, reciprocity norms, collective sense of identity in the crowdsourcing community, and the cooperative relationship network between the project and related institutions, measured using a 5-point Likert scale.

(2) Condition Variables in the Subject Interaction Dimension

Participation Motivation (MOT): measures the interestingness, challenge, and sense of meaning in crowdsourcing task design, as well as the promotion effect of incentive mechanisms provided by the project platform (such as points, leaderboards, rewards) on participation behavior, measured using a 5-point Likert scale.

Interaction Intensity (INT): evaluates the frequency and quality of interactions between different subjects (such as crowdsourcers–crowdsourcing platform, crowdsourcers–crowdsourcers, crowdsourcers–audience) in task completion, result application, feedback improvement, and other aspects, measured using a 5-point Likert scale.

(3) Condition Variables in the Value Co-creation Dimension

Digitization Performance (DIG): considers the quantity, quality, and efficiency of the project in promoting the digitization of target cultural heritage resources, measured through objective data such as the proportion of digitized collections and metadata quality assessment disclosed on project websites and in literature reports.

Crowd Innovation (CRO): assesses the contribution of new information, knowledge, and interpretations generated by crowdsourcing to cultural heritage research and interpretation, as well as the quantity and quality of derivative creative works (such as applications, artistic creations), measured by combining subjective scoring and objective data on application transformation.

Social Impact (SOI): measures the project's enhancement of public awareness of cultural heritage, the number of people participating in cultural heritage protection, and the social impact of project outcomes in education, dissemination, and reuse, measured using subjective scoring and quantitative indicators of media coverage.

(4) Outcome Variable: Project Sustainable Development (SUS)

The assessment of the overall sustainable development level of the project comprehensively considers the continuity of project operation (such as operating time, update frequency), the continuity of volunteer participation (such as number of participants, average participation duration per person), and the durability of project outcomes (such as outcome acquisition and reuse situations) [50]. The measurement method combines subjective scoring (such as project team and expert assessment) and objective indicators (such as operation duration, contribution metrics).

Based on multi-case data, the research team conducted 5-point Likert scale scoring (1—very low, 5—very high) for the seven condition variables and one outcome variable, supplemented by objective indicators as corroboration. The measurement results for each case were independently scored by 3 research team members, with the average taken as the final score for that case on the corresponding variable [51]. To ensure scoring consistency, the research team held regular calibration meetings during the case analysis process, repeatedly discussing and adjusting scoring standards to reach a consensus on the operationalization of variables [51]. Through this measurement process, the research formed a standardized score matrix of 8 variables for 18 cases, laying the data foundation for further fuzzy-set qualitative comparative analysis.

3.1.3. Data Analysis and Configuration Analysis

(1) Data Calibration

Fuzzy-set Qualitative Comparative Analysis (fsQCA) requires converting original case scores into membership scores (ranging from 0 to 1) to represent the degree to which cases belong to specific theoretical sets. This study adopted the direct calibration method, referencing past research experiences [52] to set calibration threshold standards for condition variables and the outcome variable. Specifically, cases with original scores of 5, 3, and 1 were calibrated to membership degrees of 0.95 (full membership), 0.5 (maximum ambiguity point), and 0.05 (full non-membership) for that variable, respectively. Other scores were calibrated and converted according to this standard. The calibrated membership scores better reflect the qualitative states of variables, helping to reveal differences between cases. The calibration process was completed using fsQCA 3.0 software.

(2) Single Condition Necessity Analysis

To deeply explore the influence of each single condition variable on the sustainable development performance of crowdsourcing projects, we first conducted a necessary condition analysis for both the presence and absence of condition variables. Following Ragin's (2009) suggestion, we set the consistency threshold at 0.9 and the coverage threshold at 0.5 [53]. The results of the single-condition necessity analysis are shown in Table 2.

Table 2. Analysis of the necessary conditions.

Condition	SUS_High		SUS_ Low	
	Cons_High	**Cov_High**	**Cons_Low**	**Cov_Low**
PLA	0.891892	0.871795	0.727273	0.173913
~PLA	0.310811	0.469565	0.454545	0.168067
DAT	0.891892	0.871795	0.727273	0.173913
~DAT	0.310811	0.469565	0.454545	0.168067
KNO	0.905405	0.870370	0.727273	0.170732
~KNO	0.297297	0.458333	0.454545	0.171429
SOC	0.878378	0.872727	0.772727	0.188406
~SOC	0.324324	0.480000	0.409091	0.148148
MOT	0.891892	0.868421	0.727273	0.173913
~MOT	0.310811	0.469565	0.454545	0.168067
INT	0.864865	0.888889	0.772727	0.194444
~INT	0.337838	0.480769	0.409091	0.142857
DIG	0.905405	0.859649	0.681818	0.158537
~DIG	0.297297	0.458333	0.500000	0.188679
CRO	0.878378	0.872727	0.727273	0.177215
~CRO	0.324324	0.480000	0.454545	0.164179
SOI	0.878378	0.875000	0.727273	0.177215
~SOI	0.324324	0.480000	0.454545	0.164179

~ means there is no such variable.

The necessity analysis of single conditions reveals significant insights into the factors influencing the sustainable development of cultural heritage crowdsourcing projects. For high-performance cases (Cons_High), most condition variables demonstrated strong necessity, with Knowledge Capital (KNO) and Digitization Performance (DIG) exhibiting the highest consistency scores (0.905405). This finding suggests that a solid knowledge base and substantial digitization achievements are critical prerequisites for exceptional sustainable development performance. Platform Support (PLA), Data Resources (DAT), Social Capital (SOC), Participation Motivation (MOT), Crowd Innovation (CRO), and Social Impact (SOI) all yielded consistency scores exceeding 0.85, underscoring the crucial roles of technological infrastructure, data quality, social networks, incentive mechanisms, innovative capacity, and social reputation in fostering project sustainability. These results align with existing theoretical frameworks and empirical observations. Conversely, the absence of these conditions (~condition) consistently showed low consistency scores (all below 0.34), further validating the positive causal relationships and indicating that the presence, rather than the absence, of these elements is necessary for high performance.

In the context of low-performance cases (Cons_Low), the necessity consistency scores for condition variables were generally lower than in high-performance scenarios. Social Capital (SOC) and Interaction Intensity (INT) exhibited relatively higher scores (0.772727), suggesting that insufficient trust, cooperation, and interaction among participating entities may be the primary factors hindering optimal project performance. The absence of Digitization Performance (~DIG) showed a consistency score of 0.500000, indicating that poor digitization outcomes often correlate with a lack of endogenous momentum for sustainable development. Overall, the low necessity scores for the absence of condition variables imply that the deficiency of a single factor does not inevitably lead to low performance, highlighting the complex interplay of factors influencing project sustainability and necessitating an examination of combinatorial effects among variables.

From a coverage perspective, most condition variables in high-performance cases demonstrated coverage rates exceeding 0.85, indicating their strong explanatory power for project success. In contrast, both the presence and absence of condition variables in low-performance cases exhibited low coverage rates, reflecting the limited capacity of single elements to elucidate unsuccessful cases and suggesting that the reasons for poor project performance may be more diverse.

These analyses yield several preliminary conclusions: (1) Factors such as knowledge capital and digitization performance are crucial for cultural heritage crowdsourcing projects to achieve high-level sustainable development, serving as key prerequisites for excellent performance. (2) Variables like social capital and interaction intensity, showing relatively small differences in necessity scores between high- and low-performance cases, may be fundamental factors influencing project sustainability. (3) While the presence of single-condition variables offers some explanatory power for project success or failure, it is insufficient to fully reveal the complex mechanisms of sustainable development, necessitating further investigation of combinatorial effects among variables. (4) The causes of project success or failure are multifaceted and cannot be exhaustively explained from a single perspective, requiring supplementary in-depth qualitative analysis to dynamically examine the interactions of various elements in specific contexts.

Building on these insights, the next phase of analysis will focus on sufficient condition configuration analysis, aiming to more comprehensively characterize the key combinations of elements driving the sustainable development of cultural heritage crowdsourcing projects and their differentiated impact pathways.

(3) Sufficient condition analysis and identification of key configuration

Following the necessity analysis, a sufficient condition analysis was conducted using the fsQCA method to identify key configurations leading to high and low performance in cultural heritage crowdsourcing projects. Employing standard analytical procedures and the Quine–McCluskey minimization algorithm, frequency and consistency thresholds were set at 1 and 0.8, respectively. This analysis yielded three high-performance pathways and two low-performance pathways (see Table 3).

Examination of high-performance configurations revealed that Platform Support (PLA), Data Resources (DAT), Knowledge Capital (KNO), and Digitization Performance (DIG) consistently emerged as core conditions across all pathways. This finding underscores the critical roles of technological infrastructure, data quality, knowledge management, and digitization capabilities in driving project sustainability. These results align with socio-technical systems theory, which posits that modern organizational performance stems from the dynamic evolution and interactive coupling of technical and social subsystems [54].

Concurrently, the high-performance pathways exhibited divergent combinations of peripheral conditions, including Social Capital (SOC), Participation Motivation (MOT), Interaction Intensity (INT), Crowd Innovation (CRO), and Social Impact (SOI), resulting in three distinct strategic orientations:

High-performance pathway 1 (High_1) emphasizes the significance of social networks and interactions.

High-performance pathway 2 (High_2) focuses on the synergy between incentive mechanisms and innovative capacity.

High-performance pathway 3 (High_3) highlights the combined effect of incentives and social impact.

These variations suggest that projects can adopt different development models emphasizing social capital, innovation drive, or social impact, contingent upon their core technological and knowledge capabilities. This observation exemplifies the principle of equifinality, which posits that multiple condition combinations can lead to the desired outcome [55].

Table 3. Configurations for high and low sustainability of digital humanities cultural heritage crowdsourcing projects.

Condition	SUS_High			SUS_Low	
	High_1	**High_2**	**High_3**	**Low_1**	**Low_2**
PLA	●	●	●	⊗	⊗
DAT	●	●	●	⊗	⊗
KNO	●	●	●	⊗	
SOC	○				⊗
MOT		○	○	⊗	
INT	○			⊗	
DIG	●	●	●		⊗
CRO		○			⊗
SOI			○		⊗
Consistency	0.963	0.958	0.955	0.912	0.895
Raw Coverage	0.718	0.701	0.729	0.632	0.587
Unique Coverage	0.031	0.014	0.042	0.165	0.120
Solution Consistency		0.951		0.903	
Solution Coverage		0.785		0.752	

● Indicates core condition (present); ⊗ Indicates core condition (absent); ○ Indicates a marginal condition (present); ⊙ Indicates a marginal condition (absent); Blank indicates that the condition is not important in the combination.

Low-performance configurations, conversely, exhibited distinct explanatory logic. Low-performance pathway 1 (Low_1) demonstrated that the simultaneous absence of Platform Support (PLA), Data Resources (DAT), Knowledge Capital (KNO), Participation Motivation (MOT), and Interaction Intensity (INT) is highly likely to result in project failure. This reflects the compound effect of deficiencies in technological foundations, knowledge management, participatory drive, and interaction. Low-performance pathway 2 (Low_2) further indicated that the absence of almost all factors, except Knowledge Capital, constitutes a fatal combination for project failure. These findings caution project managers against high-risk scenarios where multiple key elements deteriorate simultaneously, emphasizing the need for comprehensive attention to technological, resource, social, and managerial factors.

The juxtaposition of high-performance and low-performance pathways also revealed causal asymmetry. For instance, while Participation Motivation and Interaction Intensity played supplementary roles in high-performance pathways, their severe deficiency could be central catalysts for project failure.

(4) Theoretical Insights from Configuration Analysis

The comprehensive analysis yields the following theoretical insights:

a. Technology-Knowledge Coupling Perspective: Platform support, data resources, knowledge capital, and digitization performance emerge as core elements driving the sustainable development of cultural heritage crowdsourcing projects, constituting a technology–knowledge coupling mechanism crucial for project success. This finding extends the application of socio-technical systems theory in the digital humanities domain [56], emphasizing the decisive role of dynamic integration between technological infrastructure and knowledge resources in project performance. Future research could further explore the interactive mechanisms between technological and knowledge factors, delineating the technology-enabled pathways and knowledge transformation models in cultural heritage crowdsourcing amid digital transformation. Additionally, this insight provides a theoretical foundation for system dynamics modeling, indicating that model construction should prioritize capturing feedback connections among key variables such as platform support, data resources, knowledge capital, and digitization performance.

b. Moderating Role of Social Factors: While social factors like participation motivation and interaction intensity are not sufficient or necessary conditions for project success, they play crucial "lubricating" and "catalytic" moderating roles in consolidating participatory drive and facilitating human–machine interaction. This finding resonates with researchers' growing attention to social capital and participation mechanisms in cultural heritage crowdsourcing projects, highlighting the importance of balancing social dimensions alongside technological drivers. For system dynamics modeling, this implies the need to incorporate social factors into feedback structures, simulating their interactive effects with technological and knowledge factors, and examining the dynamic changes in project sustainability under various social contexts and participatory environments.

c. Organizational Innovation Driving Mechanisms: Elements such as social capital, innovative capacity, and social impact serve as pivotal leverage points for projects to achieve differentiated and sustainable development based on core capabilities, reflecting diverse mechanisms of organization-driven innovation. This insight aligns with absorptive capacity theory regarding organizations' integration of external new knowledge for innovation [57], revealing diverse pathways for cultural heritage crowdsourcing projects to achieve innovative breakthroughs and sustainable development through cross-boundary collaboration, creative integration, and reputation accumulation. From a system dynamics perspective, this necessitates designing feedback loops for organizational learning and innovation, exploring how factors like social capital accumulation, enhancement of innovative capacity, and expansion of social impact form virtuous cycles for project sustainable development.

d. Collaborative Governance of Multiple Stakeholders: The organic combination and dynamic balance of resource support, stakeholder interests, and value co-creation are key to project sustainable development, reflecting the importance of collaborative governance among multiple stakeholders. This finding echoes stakeholder theory, emphasizing that project sustainable development requires balancing the interests of diverse entities including participants, organizers, audiences, and the general public [58], achieving continuous creation of shared value through inclusive participation and collaborative innovation. This insight suggests that system dynamics modeling should thoroughly characterize strategic interactions among stakeholders, balance multiple objectives dynamically in different scenarios, simulate the evolutionary paths of collaborative governance structures, and explore sustainable development models of mutual benefit and positive resonance.

These theoretical insights, on one hand, corroborate the limitations of existing technological and participatory perspectives, emphasizing the need to systematically examine the generative mechanisms of sustainable development in cultural heritage crowdsourcing projects from socio-technical coupling, organization-driven innovation, and multi-stakeholder perspectives. On the other hand, they pose new requirements and directions for system dynamics modeling, calling for model construction to focus on characterizing key influencing factors and their interactions, simulating organizational innovation and individual participatory behaviors, and modeling stakeholder game equilibria, aiming to comprehensively reproduce the dynamic complexity of sustainable development.

3.2. Development of System Dynamics Simulation Model

3.2.1. Model Boundary Determination and Key Variable Definition

The fsQCA analysis revealed how key elements and their combinations in resource synergy, subject interaction, and value co-creation influence the sustainable development of cultural heritage crowdsourcing projects. To further explore the dynamic interaction mechanisms of these elements, this study employs a system dynamics approach to model and simulate the sustainable development process of cultural heritage crowdsourcing projects, guided by the "Resource Synergy–Subject Interaction–Value Co-creation" analytical framework.

Initially, the system dynamics model boundary was delineated as the internal operational system of cultural heritage crowdsourcing projects, based on the research objectives and problem boundaries. This boundary definition was predicated on the following considerations: (1) focusing on the project's micro-operational processes, aligning with research goals; (2) corresponding to the three dimensions in the theoretical analysis framework; (3) facilitating the incorporation of key influencing factors identified in the fsQCA analysis; and (4) moderately simplifying model complexity to highlight primary dynamic mechanisms [59]. Within this boundary, the system dynamics model primarily simulates the dynamic behaviors and interactive influences of three subsystems: resource synergy, subject interaction, and value co-creation, to elucidate the endogenous driving mechanisms of project sustainable development.

Subsequently, key variables for each subsystem were identified based on the theoretical framework and fsQCA results. The variable selection criteria included the following: (1) reflection of core elements and key processes within each subsystem; (2) correspondence with necessary and sufficient conditions identified in the fsQCA analysis; (3) representation of major stakeholder concerns and performance indicators; and (4) operational feasibility and data availability.

In the resource synergy subsystem, key variables incorporated include platform support capability, data resource quality, knowledge capital stock, and social capital stock. The fsQCA results indicated that platform support and data resources are necessary conditions for project sustainable development, while knowledge capital and social capital reflect the differentiation in successful pathways across cases. These variables embody the critical resource foundations upon which crowdsourcing projects depend for survival and development [60], corresponding to the resource dimension in the theoretical framework.

For the subject interaction subsystem, key variables encompass participant numbers, participation willingness, task completion rate, and interaction frequency. The fsQCA analysis revealed participation motivation and interaction intensity as crucial factors influencing project sustainable development. These variables characterize the scale, motivation, and performance features of the crowdsourcing participation process [61], reflecting the subject interaction dimension of the theoretical framework.

Key variables in the value co-creation subsystem involve the quantity of digitization outcomes, level of knowledge innovation, and social impact. The fsQCA results emphasized digitization performance, knowledge innovation, and social impact as critical outcome dimensions for project sustainable development, representing the effectiveness and output of crowdsourcing activities [62]. These variables align with the value creation dimension of the theoretical framework.

In conclusion, based on the "Resource Synergy–Subject Interaction–Value Co-creation" framework and incorporating fsQCA research findings, the boundaries and key variables of the system dynamics model have been defined. On one hand, the included variables comprehensively reflect critical aspects of cultural heritage crowdsourcing projects' operations, including resource foundations, process characteristics, and performance outcomes, providing a solid conceptual basis for characterizing the dynamic complexity of project sustainable development. On the other hand, the key variables correspond to the necessary conditions and typical configurations identified in the preliminary fsQCA analysis, establishing an effective link between qualitative analysis and quantitative modeling, and providing a theoretical foundation for establishing model causality [63].

3.2.2. Causal Loop Diagrams of Subsystems and Their System Dynamics Modeling Simulation

Following the identification of key influencing factors and dynamic hypotheses for the sustainable development of cultural heritage crowdsourcing projects, system dynamics modeling and simulation analysis were conducted. Initially, eight key variables were identified and integrated based on the causal loop diagrams: social impact, platform support capability, data resource quality, knowledge capital, social capital, number of participants, participation willingness, and task completion rate. These variables interact through complex feedback mechanisms, forming multiple dynamic causal chains.

(1) Causal Relationship Mechanisms of Subsystems

Causal loop diagrams were utilized to describe the causal relationships and feedback mechanisms among internal system variables. Based on literature analysis and case studies, the following primary causal relationships were identified:

In the resource synergy subsystem, platform support capability enhances task completion rate and interaction frequency by optimizing task publishing, review, and interaction mechanisms (e.g., intelligent task recommendation, quality control, incentive mechanisms). This forms a cross-system positive feedback loop R1: "platform support capability → task completion rate/interaction frequency → subject interaction". The improvement of data resource quality helps attract more volunteers to participate in digitization tasks (positive feedback loop R2: "data resource quality → number of participants → task completion rate → quantity of digitization outcomes") and provides richer materials for knowledge innovation ("data resource quality → level of knowledge innovation" causal chain). Additionally, knowledge capital stock can enhance project social impact and participation willingness by accumulating project experience and cultivating expert communities, forming a cross-cycle positive feedback loop R3: "knowledge capital stock → social impact/participation willingness → number of participants". Social capital stock provides continuous momentum for resource mobilization and outcome application through trust mechanisms and stable cooperative relationships, supporting sustainable project operation (causal chain: "social capital stock → resource mobilization/outcome application → project sustainability").

The core of the subject interaction subsystem is the mutual promotion between the number of participants and participation willingness (positive feedback loop R4: "number of participants ↔ participation willingness"), jointly driving the improvement of task completion rate and interaction frequency. While the increase in digitization outcomes directly depends on the task completion rate, its accumulation further drives knowledge innovation (causal chain: "quantity of digitization outcomes → level of knowledge innovation"), triggering a cross-cycle positive feedback loop R5: "level of knowledge innovation → social impact → participation willingness → number of participants → task completion rate → quantity of digitization outcomes".

Finally, a mutually reinforcing positive feedback relationship exists between the level of knowledge innovation and social impact (positive feedback loop R6: "level of knowledge innovation ↔ social impact"), jointly determining the project's endogenous momentum and external reputation for sustainable development [64].

This comprehensive analysis of the causal loop diagram highlights the following theoretical insights:

(1) Multiple positive feedback relationships exist among internal elements of the resource synergy, subject interaction, and value co-creation subsystems, collectively shaping the endogenous growth mechanism for the sustainable development of cultural heritage crowdsourcing projects.
(2) Cross-subsystem causal chains and feedback loops reveal the dynamic interactive influences among the three subsystems. For example, resource synergy affects subject behavior through task design optimization and knowledge capital accumulation, subsequently influencing value creation performance.
(3) The presence of cross-cycle positive feedback loops (e.g., R3, R5) indicates path dependence and positive promotion effects of later-stage resource accumulation, experience sedimentation, and reputation building on future development.

These findings, building upon the earlier fsQCA results, further elucidate the operational mechanisms of key elements such as resources, subjects, and value in driving project sustainable development, complementing configuration theory in the following ways:

a. Configuration elements are not static combinations in project operation but engage in dynamic interactions.

b. The impact of various configuration elements on project development involves a combination of immediate and cumulative effects.
c. The effects of element combinations exhibit path dependence and positive feedback self-reinforcing effects.

Therefore, fully recognizing and grasping this dynamic complexity is crucial for achieving sustainable project development [65].

3.2.3. Analysis of Simulation Results

The numerical simulation of the system dynamics model yielded dynamic evolution results for cultural heritage crowdsourcing projects under various parameter combinations (as shown in Figure 2). The simulation results reveal the dynamic patterns of key variables such as platform support capability, data resource quality, knowledge capital, social capital, number of participants, participation willingness, task completion rate, and digitization outcomes under different scenarios, providing rich quantitative information for explaining the influence mechanisms of project sustainable development [66].

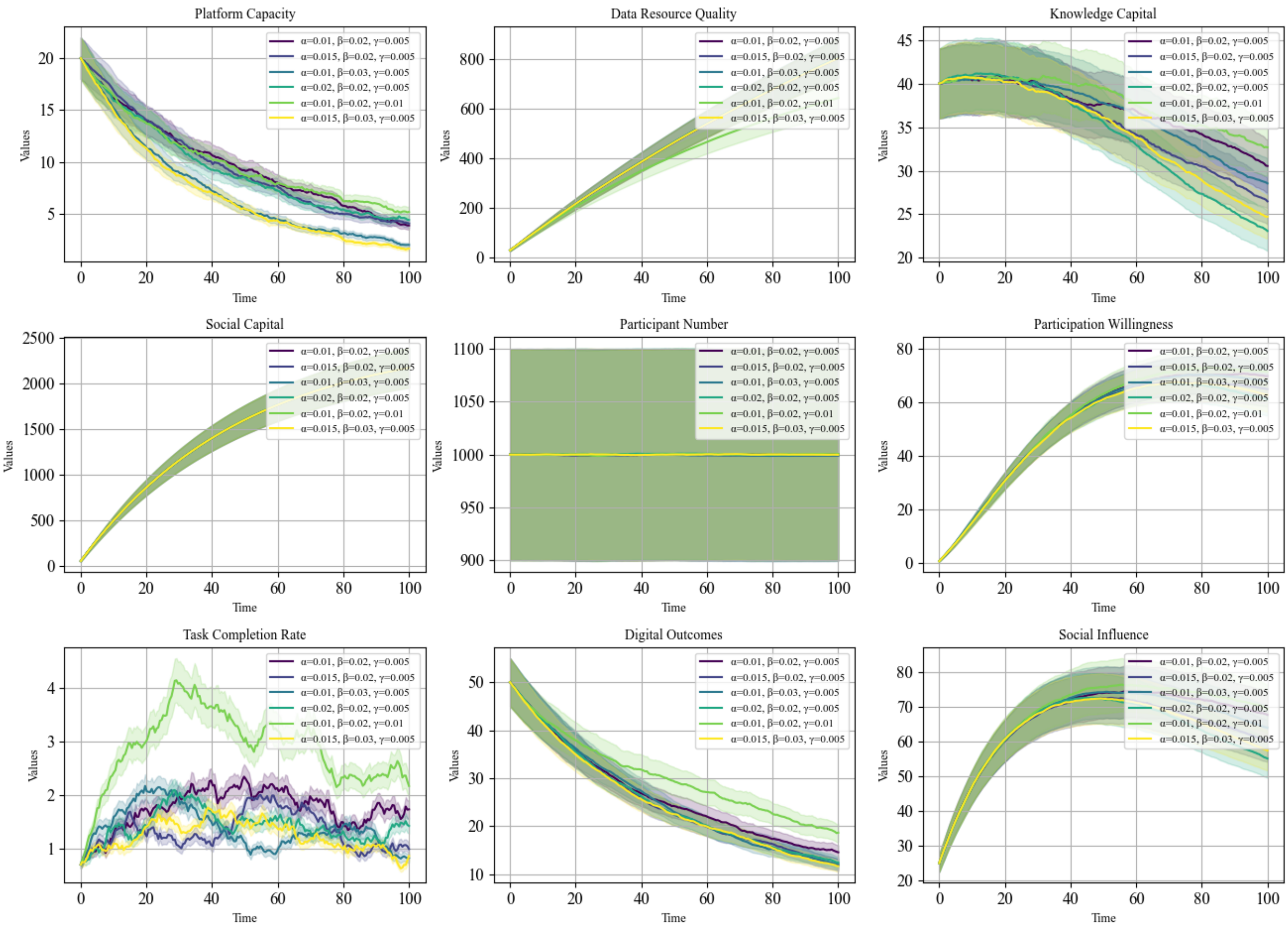

Figure 2. Simulation results of system dynamics of digital humanities cultural heritage crowdsourcing projects.

Specifically, regarding platform support capability, as parameters α and β increase, the platform capability exhibits a faster growth trend and a higher steady-state level. This indicates that measures such as optimizing task mechanisms and enhancing user experience can effectively improve the platform's support capacity for crowdsourcing activities, injecting sustained momentum into the project. The change in data resource quality demonstrates a dynamic characteristic of initial decline followed by improvement, attributable to the initial scarcity of participants leading to data resource degradation, while quality gradually improves and stabilizes as participation increases and platform capabilities enhance. This highlights the importance of participation incentives and technological upgrades in ensuring data quality.

Knowledge capital and social capital, as core intangible assets of the project, show growth trends closely related to α and β. Knowledge capital exhibits significant S-shaped growth characteristics, indicating that as crowdsourcing activities deepen, knowledge accumulation and innovation effects continuously accumulate, forming a self-reinforcing positive feedback loop. The accumulation of social capital, however, depends more on interaction and trust-building among participants, showing a relatively slow but consistently improving evolutionary trend.

In terms of subject interaction, the number of participants and participation willingness display synchronized evolution. Improvements in platform capabilities and expansion of social impact brought about by parameter changes can effectively promote the increase in participation scale and enthusiasm. Notably, participation willingness shows some fluctuations, possibly related to the dynamic matching between participants' intrinsic motivation and external incentives, requiring sensitivity and responsiveness in operation. The task completion rate, a key indicator measuring participation performance, benefits from the joint drive of participant numbers and willingness but is also significantly influenced by the platform's technical capabilities and data quality.

Regarding value creation, digitization outcomes represent the core output of crowdsourcing activities, with growth trends closely related to task completion rates and knowledge accumulation. Efficiency improvements and innovation accumulation brought by parameter changes can significantly enhance both the quantity and quality of outcomes. Social impact reflects the project's spillover effects and reputation effects, driven by both knowledge capital and digitization outcomes, showing a trend of continuous expansion.

This comprehensive analysis reveals that although key variables exhibit different dynamic change patterns due to their inherent characteristics and subsystem locations, they influence each other through complex feedback mechanisms, collectively shaping the overall development trend of cultural heritage crowdsourcing projects. The dynamic complexity demonstrated by the simulation results provides new insights for understanding project operations from a systemic perspective.

3.2.4. Theoretical Correspondence between Simulation Results and fsQCA Findings

A comparison of the simulation results with the preceding theoretical analysis reveals substantial consistency and complementarity. On one hand, the system dynamics simulation results validate the rationality of the "Resource Synergy–Subject Interaction–Value Co-creation" framework and support the key influential factor configurations revealed by the fsQCA analysis. For instance, variables such as platform capability, data quality, knowledge capital, and participation willingness invariably emerge as critical factors driving project sustainable development, corroborating the necessary conditions highlighted in the fsQCA results. Furthermore, the differentiated combinations of variables like social capital and social impact with other elements form diverse sustainable development pathways, such as resource-driven and innovation-driven approaches, echoing the sufficient condition configurations revealed by fsQCA.

On the other hand, the system dynamics analysis further elucidates the complex interactive effects of influencing factors in dynamic evolution. By observing system behavior differences under various parameter combinations, we can more clearly identify the sensitivity of each variable, the operational mechanisms of key feedback loops, and the conditions for emergent behaviors, contributing to a deeper understanding of project dynamic mechanisms. For example, the simulation results demonstrate phenomena such as the dynamic oscillation characteristics of data resource quality, the periodic exponential growth of knowledge capital, and the synchronized evolution of social capital and participation willingness. These observations transcend the theoretical hypotheses from a static perspective, highlighting the uniqueness of crowdsourcing projects as complex adaptive systems.

4. Discussion

4.1. Research Summary

This study's findings validate and extend the "Resource Synergy–Subject Interaction–Value Co-creation" theoretical framework in the context of cultural heritage crowdsourcing projects. Our analysis reveals several key insights:

In terms of empirical research, this paper employs the fsQCA method to conduct a systematic comparative analysis of 18 typical cases. The findings reveal the following: (1) Factors such as platform support, data resources, knowledge capital, and digitization performance are necessary conditions for project sustainable development. (2) Factors like social capital, participation incentives, innovation drive, and social impact form multiple sufficient condition pathways toward sustainable development through differentiated combinations, exhibiting characteristics such as "resource-driven" and "innovation-driven". (3) The dynamic changes and compound effects of conditional factors have a continuous shaping effect on project sustainable development. Overall, the fsQCA analysis validates the explanatory power of the theoretical framework, revealing characteristics such as non-single determinants, non-linear evolution, and multi-path patterns of crowdsourcing project success, providing a configurational perspective for understanding project sustainable development [67].

Building on the revelation of static influencing factor configurations, this study further employs system dynamics methods to characterize the complex interactive effects of various elements in dynamic evolution. The simulation results demonstrate the dynamic evolutionary patterns of variables such as platform support, data quality, knowledge capital, participation willingness, task performance, and innovation outcomes under different scenarios. They reveal self-reinforcing mechanisms in key links such as participation incentives and task completion, innovation accumulation and social impact, as well as structural differences in the system under different parameter spaces. These findings deepen our understanding of the dynamic, adaptive, and emergent characteristics of crowdsourcing projects as complex adaptive systems, providing new analytical dimensions for interpreting the influence mechanisms of condition configurations.

4.2. Theoretical Contributions

This study makes several contributions to the understanding of sustainable development mechanisms in digital humanities cultural heritage crowdsourcing projects, addressing the research questions posed in the Introduction:

(1) Addressing research question ①, the fsQCA analysis reveals that platform support, data resources, knowledge capital, and digitalization performance constitute necessary conditions for project sustainability. In contrast, factors such as social capital, participant motivation, innovation drive, and social impact form multiple sufficient pathways to sustainability through differentiated combinations, exhibiting patterns such as "resource-driven" and "innovation-driven". These findings challenge the linear, single-path assumptions in traditional explanatory models of crowdsourcing phenomena, highlighting the importance of a configurational perspective in understanding the sustainable development of crowdsourcing projects.

(2) Regarding research question ②, system dynamics modeling uncovers the non-linear feedback mechanisms and emergent behaviors in the dynamic evolution of crowdsourcing systems. The self-reinforcing effects in key links, such as participation incentives–task completion and innovation accumulation–social impact, drive project sustainability. This indicates that as a complex adaptive system, the intrinsic development logic of crowdsourcing projects needs to be understood from a dynamic, process-oriented perspective, with resource endowments, action strategies, and value returns intertwined in shaping the emergent evolution of the system.

(3) Concerning research question ③, the "Resource Synergy–Stakeholder Interaction–Value Co-creation" analytical framework integrates resource-based view, stakeholder theory, and value co-creation theory, providing a comprehensive theoretical lens for examining the complex factors driving crowdsourcing project sustainability. By combining fsQCA and SD methods, this study systematically interprets the generative mechanisms between condition configurations and outcomes from both static comparison and dynamic simulation dimensions, demonstrating the framework's theoretical explanatory power in deciphering the underlying logic of crowdsourcing project sustainability. This has important implications for expanding research horizons and enriching methodological tools in the digital humanities field.

Overall, by synergizing configurational analysis and system dynamics, this paper provides a relatively comprehensive account of the influence mechanisms underlying the sustainable development of cultural heritage crowdsourcing projects from both static and dynamic perspectives. On one hand, deconstructing and typifying condition configurations reveals the differentiated effects of combinatorial matches among resource supply, stakeholder action, and value return factors in driving project sustainability. On the other hand, through simulating dynamic feedback and emergent behaviors, it further uncovers the complex effects of factor combinations in temporal evolution, extending the spatiotemporal boundaries of configurational explanations. This dual-perspective analytical approach systematically disentangles the enigma of success and failure in cultural heritage crowdsourcing projects from an extended spatiotemporal dimension, offering significant inspiration for theoretical advancements in the digital humanities domain.

5. Conclusions

5.1. Summary of Research Findings

Based on the comprehensive analysis, this study draws the following main conclusions:

(1) The sustainable development of digital humanities cultural heritage crowdsourcing projects is influenced by multiple heterogeneous factors interacting with each other. The "Resource Synergy–Subject Interaction–Value Co-creation" analytical framework, constructed based on resource-based theory, stakeholder theory, and value co-creation theory, provides a comprehensive theoretical perspective for explaining these influencing factors. This framework incorporates multiple analytical dimensions such as resources, actions, and performance, extending and complementing traditional theoretical models that focus on single aspects. Under different configurations of resource endowments, action strategies, and value demands, differentiated successful pathways such as "resource-driven" and "innovation-driven" emerge, highlighting the non-homogeneous, multi-causal, and non-linear characteristics of crowdsourcing project success.

(2) Core elements driving project sustainable development, such as platform support, data resources, knowledge capital, and participation willingness, exhibit significant non-linear feedback effects. Through mechanisms like self-reinforcement and dynamic adaptation, they collectively shape the project's emergent evolution. The fsQCA analysis reveals that different factor configurations can achieve the same successful results through differentiated paths ("equifinality"), while seemingly similar factor combinations may produce divergent evolutions due to dynamic changes and external contextual influences. This implies that explaining and predicting project success or failure cannot simply rely on finding "success factors" but should examine system development from a more dynamic and integrated perspective.

(3) The intrinsic mechanism of project sustainable development manifests as a multi-level, dynamic complex system. It involves the intertwined interaction of various factors including individual micro-behaviors (e.g., participation motivation), group emergent effects (e.g., task performance), organizational resource regulation (e.g., platform governance), and cross-domain value feedback (e.g., reputation enhancement), requiring comprehension from a holistic perspective. The system dynamics analysis

reveals that the resource–action–performance causal chain driving project sustainable development has characteristics such as dynamic adaptability, non-linearity, and emergence. Project success depends not only on initial conditions and static resource allocation but also on the dynamic synergy of resources, behaviors, and goals in changing environments.

(4) Promoting the sustainable development of cultural heritage crowdsourcing projects requires systematic design of key influencing factors. This involves emphasizing foundational capabilities such as resource supply and platform construction, focusing on developmental drivers like participation incentives and innovation mechanisms, and coordinating diverse stakeholders to foster a positive ecosystem. Simultaneously, adaptive adjustments at key nodes are necessary to guide the system toward healthy evolution. The feedback, cumulative, and lag effects of causal mechanisms, and the adaptive and emergent nature of subject behavior, result in complexities such as path dependence, equilibrium evolution, and critical transitions under different conditions. These insights enrich the understanding of crowdsourcing projects as complex adaptive systems, providing important supplements to traditional research approaches based on static assumptions.

5.2. Practical Implications

First, the research results emphasize that the foundation of project sustainable development is resource supply capacity, including platform support, data resources, knowledge capital, and social capital. This implies that project teams should highly prioritize the construction of infrastructure such as technical architecture, data governance, knowledge management, and reputation management as priority areas for project development. Resource allocation should be planned with the concepts of openness, collaboration, and sharing, focusing on optimizing integration and fluid sharing while gathering diverse internal and external resources.

Second, the research reveals the key role of subject interaction in stimulating participation enthusiasm and promoting innovation emergence. This suggests that project teams should focus on creating an open, trusting, and collaborative participation environment, investing effort in participation convenience, task attractiveness, and interaction friendliness to stimulate the endogenous motivation of diverse subjects. Social networking and gamification approaches can be leveraged to enrich the emotional experience of participation and enhance value identification.

Third, the research highlights the significant impact of value co-creation on long-term project performance. This requires project teams to adopt systematic thinking, focusing more on the sustainable creation of multiple value dimensions such as knowledge innovation and social impact while producing digitized outcomes. An open crowdsourcing ecosystem can be constructed to achieve the diffusion and application of project results across multiple domains, driving innovative development in academic research, creative production, and social education.

Fourth, the research emphasizes that promoting project sustainable development requires attention to dynamic management, adapting to changes in internal and external environments, and implementing system regulation at key nodes. This suggests that project teams should maintain agility and foresight, timely optimizing platform functions, incentive mechanisms, and task settings to guide system evolution along expected goals. Simultaneously, they should be adept at capturing opportunities brought by environmental changes and actively shaping a favorable development ecosystem.

Finally, from a more macro perspective, this research has implications for exploring sustainable development paradigms in cultural heritage protection and digital humanities research. The study shows that crowdsourcing-based cultural heritage digitization is not merely a technological application but an ecosystem construction process involving multiple subjects and complex value logics. In the current context of widespread digital technology empowerment, cultural heritage work should be based on building an open, collaborative, and sustainable crowdsourcing ecosystem, fully gathering social forces, innovating supply methods, expanding value boundaries, and achieving the dynamic inheritance of heritage resources. This requires us to explore sustainable development system solutions beyond single project practices, supported by multidisciplinary knowledge systems such as cultural heritage studies, digital humanities, and information science.

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