Journal of Posthumanism
2025
Volume: 5, No: 4, pp. 815–839
ISSN: 2634-3576 (Print) | ISSN 2634-3584 (Online)
posthumanism.co.uk

DOI: https://doi.org/10.63332/joph.v5i4.1134

A Review of the Research on the Decision-Making Framework for Optimizing Rural Building Spatial Layout Based on Multi-Source Data Fusion: A Case Study of Hebei Province

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Abstract

This paper systematically reviews the research progress of rural building spatial layout optimization decision-making based on multi-source data fusion, and discusses it with Hebei Province as a case study. Multi-source data fusion technology provides a new methodological framework for the study of rural building spatial layout, which can integrate multi-dimensional information such as remote sensing images, geographic information system data, socio-economic statistics and field survey data, and comprehensively analyze the characteristics of rural building space and its influencing factors. By reviewing relevant research results at home and abroad, this paper summarizes the application methods, evaluation systems and optimization strategies of multi-source data fusion in the study of rural building spatial layout, and constructs a comprehensive decision-making framework. Combined with the specific case of Hebei Province, the regional characteristics, existing problems and optimization directions of the rural building spatial layout in the region are analyzed, and a differentiated spatial layout optimization path based on multi-scenario analysis is proposed. The study shows that the decision-making framework based on multi-source data fusion can effectively support the scientific evaluation and optimization of rural building spatial layout, and provide theoretical basis and technical support for the implementation of the rural revitalization strategy and the improvement of rural living environment.

Keywords: *Multi-Source Data Fusion, Rural Buildings, Spatial Layout, Optimization Decision Framework, Hebei Province, Review.*

Introduction

With the rapid advancement of urbanization and the in-depth implementation of the rural revitalization strategy, the optimization of rural building space layout has become a key link in improving the quality of rural living environment and promoting rural sustainable development (Long et al., 2016). The rural building space layout is not only related to the convenience of farmers' production and life, but also affects the rural landscape, ecological environment quality and regional development efficiency (Liu et al., 2017). In China, the rural building space layout has long been plagued by problems such as disorderly expansion, waste of resources, and weakening of cultural characteristics. It is urgent to build a scientific and reasonable optimization decision-making framework (Yang et al., 2020).

Traditional studies on rural building spatial layout are mostly based on a single data source, such as remote sensing image interpretation or questionnaire surveys, which are difficult to fully reflect the complexity of rural building spatial layout (Wang et al., 2019). In recent years, the development of information technologies such as big data, the Internet of Things, and cloud

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computing has provided technical support for multi-source data acquisition and fusion (Li et al., 2018), making it possible to analyze rural building spatial layout from multiple dimensions and scales. Multi-source data fusion methods can integrate remote sensing images, GIS data, socioeconomic statistics, historical documents, and field survey data to build a more comprehensive and accurate rural building spatial layout optimization decision framework (Zhang et al., 2021).

Hebei Province is a typical agricultural province in northern China. Its rural areas are distributed in various geographical units such as the edge of the Beijing-Tianjin-Hebei metropolitan area, the Taihang Mountains, the Yanshan Mountains, and the North China Plain. The spatial layout of rural buildings shows obvious regional differences (Song et al., 2020). With the in-depth implementation of the coordinated development strategy of Beijing-Tianjin-Hebei, rural areas in Hebei Province are facing multiple tasks such as industrial transformation and upgrading, ecological environmental protection, and traditional village protection (Zhao et al., 2021), which puts forward higher requirements for the optimization of rural building spatial layout. Therefore, taking Hebei Province as the research object, exploring the decision-making framework for optimizing the spatial layout of rural buildings based on multi-source data fusion has important theoretical value and practical significance.

This paper aims to systematically review the application progress of multi-source data fusion in the research of rural building space layout optimization decision-making, analyze the methods, technologies and application cases of multi-source data fusion, explore the rural building space layout evaluation index system and optimization strategy based on multi-source data fusion, and take Hebei Province as an example to discuss the application prospects of this framework, so as to provide theoretical reference and methodological reference for promoting the improvement of rural living environment and rural revitalization.

Research Progress on Rural Building Space Layout

Concept and Characteristics of Rural Building Space Layout

Rural architectural spatial layout refers to the distribution pattern and organization of various types of buildings in rural areas in geographical space, which is the spatial result of human adaptation to and transformation of the natural environment (Antrop, 2004). Compared with the urban architectural spatial layout, the rural architectural spatial layout has the following characteristics: first, it is highly dependent on nature and is significantly affected by natural conditions such as topography, climate, and hydrology (Banski & Wesolowska, 2010); second, it has obvious cultural continuity, and cultural factors such as traditional culture, family structure, and folk customs have a profound impact on spatial form (Rapoport, 2016); third, it has a high degree of mixed economic functions, and production and living functions are often intertwined (Woods, 2010); fourth, it has great spatial heterogeneity, and different regions present different spatial patterns due to differences in natural conditions, economic development, and cultural traditions (Long et al., 2012).

The research dimensions of rural building spatial layout mainly include morphological characteristics, functional organization, spatial structure and evolutionary mechanism. From the perspective of morphology, researchers focus on indicators such as building density, morphological compactness, and spatial distribution pattern (Dong et al., 2016); from the perspective of functional organization, they focus on the configuration and coordination of production, living, and ecological space (Li et al., 2016); from the perspective of spatial structure, they focus on spatial relationships such as core-edge structure and network structure (Tacoli, 2003); from the perspective of evolutionary mechanism, they focus on the driving factors and action paths that affect the changes in rural building spatial layout (Tan & Li, 2013).

Research on Factors Affecting Rural Building Space Layout

The factors that affect the spatial layout of rural buildings are complex and diverse. Existing research mainly explores the issues from the dimensions of natural environment, social economy, policy system and technological progress.

In terms of natural environmental factors, topography, climate conditions, hydrological characteristics and land resources are considered to be the basic factors affecting the spatial layout of rural buildings (Zhang et al., 2014). For example, Holmes' (2010) study of rural settlements in Australia showed that terrain undulation and water availability directly affect the spatial distribution pattern of rural buildings; Liu et al. (2013) found that the spatial layout of rural buildings in China is significantly correlated with terrain factors such as altitude and slope. The building density in plain areas is high and concentrated, while the building density in mountainous areas is low and dispersed.

In terms of socioeconomic factors, population changes, economic development, industrial structure and transportation conditions are considered to be key factors affecting the spatial layout of rural buildings (Tan et al., 2018). Irwin & Bockstael (2004) found a positive correlation between population density and rural building density through their study of rural areas in Maryland, USA; Zhou et al. (2013) pointed out that the spatial layout of rural buildings in economically developed areas of China is more compact, while that in economically underdeveloped areas is more scattered; Li et al. (2018) confirmed through their study of the North China Plain that transportation accessibility has a significant impact on the spatial distribution of rural buildings.

In terms of policy and institutional factors, land system, planning policy and development strategy have a profound impact on the spatial layout of rural buildings (Long et al., 2016). Long & Liu (2016) analyzed the impact of China's land system reform on the spatial layout of rural buildings and found that the land use rights transfer mechanism under the collective land ownership system affects the expansion pattern of rural buildings; Song et al. (2019) showed that the construction of new countryside and the rural revitalization strategy promoted the optimization and reorganization of the spatial layout of rural buildings in China.

In terms of technological progress, the development of building materials, construction technology and information technology has changed the spatial layout of rural buildings (Siciliano, 2012). Yang et al. (2015) pointed out that the popularization of modern building materials and technologies has made the spatial layout of rural buildings no longer strictly limited to local materials and traditional crafts; Wang et al. (2020) found that the development of information technology is reshaping rural production and lifestyle, which in turn affects the demand for building space and layout patterns.

Research on Optimization Methods of Rural Building Space Layout

In order to optimize the spatial layout of rural buildings, scholars have proposed a variety of methods and technical paths, mainly including GIS-based spatial analysis methods, multi-objective planning methods, participatory planning methods and scenario simulation methods.

GIS-based spatial analysis methods are one of the most widely used methods in the study of rural building spatial layout optimization. Chen et al. (2014) used spatial autocorrelation analysis and kernel density estimation methods to identify the spatial agglomeration characteristics of rural buildings in the eastern coastal areas of China and proposed optimization strategies; Ma et al. (2018) combined the geographically weighted regression (GWR) model to analyze the regional differences in factors affecting the spatial layout of rural buildings, providing support for optimization decisions based on local conditions; Hao et al. (2021) applied space syntax theory to analyze the topological structure characteristics of rural building spatial layout and optimized the spatial organization model.

Multi-objective planning methods focus on balancing multiple objectives in optimizing the spatial layout of rural buildings. Zhou et al. (2017) constructed a planning model that includes three objectives: ecological protection, economic benefits, and social equity, and optimized the spatial layout of rural buildings in the Yangtze River Delta. Li et al. (2019) applied the analytic hierarchy process and fuzzy comprehensive evaluation method to establish a multi-objective evaluation system for the spatial layout of rural buildings, and proposed a priority development zone division scheme. Wang et al. (2021) combined simulated annealing algorithm and genetic algorithm to achieve multi-objective optimization of rural building spatial layout.

The participatory planning method emphasizes the participation and decision-making role of stakeholders in the optimization of rural building space layout. Scott (2011) proposed a rural planning framework based on community participation, emphasizing the dominant position of villagers in spatial layout decision-making; Zhang et al. (2016) achieved the co-construction and sharing of rural building space layout by building a multi-party interest coordination mechanism; Yang et al. (2020) designed a rural spatial planning method based on the public participatory geographic information system (PPGIS), which improved the democracy and scientificity of planning decisions.

The scenario simulation method focuses on the impact of future uncertainty on the spatial layout of rural buildings. Song et al. (2020) simulated the evolution trend of rural building spatial layout in northern China under different development scenarios based on cellular automata and multi-agent models; Liu et al. (2021) constructed a scenario analysis framework that included factors such as climate change, population mobility, and policy changes, and predicted the changes in rural building spatial layout under various scenarios; Zhao et al. (2022) used a system dynamics model to analyze the impact of different development paths on the spatial layout of rural buildings in the Beijing-Tianjin-Hebei region.

Application Of Multi-Source Data Fusion in the Study of Rural Building Spatial Layout

Multi-Source Data Types and Characteristics

With the development of data acquisition technology, the data sources available for research on rural building spatial layout are becoming increasingly rich, mainly including remote sensing image data, GIS spatial data, socioeconomic statistical data, questionnaire data, and crowd-source geographic data (Li et al., 2019).

Data Types	Main data sources	Spatial and temporal characteristics	Advantages	limitation	Representative Applications

Remote sensing image data	Satellite imagery, aerial imagery, drone imagery	High temporal and spatial resolution, capable of acquiring large-scale spatial information	Objective, comprehensive, timely and periodic	Affected by weather, the accuracy of object recognition is limited	Rural building space morphology extraction and land use change monitoring
GIS spatial data	Topographic maps, thematic maps, vector data	High spatial accuracy and rich attribute information	Intuitive spatial expression, easy for spatial analysis	High data acquisition cost and long update cycle	Spatial relationship analysis, suitability evaluation, accessibility analysis
Socioeconomic statistics	Statistical yearbooks, census data, departmental statistics	The time series is long and the spatial scale is mostly administrative units	Strong systematicity and good comparability	Low spatial resolution, difficult to reflect internal differences	Socio-economic background analysis, driving force exploration, and development trend forecasting
Questionnaire data	Field research, interviews, questionnaires	Updated in a timely manner, reflecting the specific regional situation in detail	Rich in information, able to obtain subjective evaluation	The sample size is limited and representativeness is limited	Residents' needs analysis, satisfaction evaluation, and behavioral characteristics analysis
Crowd-sourced geographic data	Social media, mobile location, volunteer geo-information	Strong real-time performance and microscopic scale	Reflects the characteristics of human activities and has a large amount of data	Lots of noise, varying quality	Activity space analysis, human-land relationship research, hotspot identification

Table 1: Commonly Used Multi-Source Data Types and Characteristics in the Study of Rural Building Spatial Layout

Remote sensing image data plays a fundamental role in the study of rural building spatial layout.

Liu et al. (2013) used multi-temporal Landsat images to analyze the expansion pattern and spatiotemporal evolution characteristics of rural building land in China; Zheng et al. (2017) combined high-resolution satellite images and drone aerial photography to finely identify the architectural layout and morphological characteristics of traditional villages; Yang et al. (2020) used night light data to detect the spatiotemporal changes in the intensity of construction activities in rural areas of China.

GIS spatial data provides rich spatial information for the analysis of rural building spatial layout. Chen et al. (2015) analyzed the impact of terrain factors on rural building layout based on digital elevation model (DEM) and water system data; Wang et al. (2018) used road network data to study the spatial correlation between traffic accessibility and rural building density; Li et al. (2021) combined land use data and ecological function zoning to evaluate the ecological and environmental impact of rural building layout.

Socioeconomic statistics provide a basis for understanding the socioeconomic background of rural building spatial layout. Zhou et al. (2016) used census data to explore the relationship between population change and rural building land expansion; Song et al. (2019) analyzed the impact of regional economic differences on rural building forms based on economic development indicators; Zhang et al. (2022) combined industrial structure data to study the mechanism of industrial transformation on the functional reorganization of rural buildings.

Questionnaire data can deeply reflect the needs and behavioral characteristics of rural residents. Scott et al. (2015) revealed the impact of changes in family structure on rural residential space demand through interviews with farmers; Li et al. (2018) evaluated the social benefits of rural building space layout based on a resident satisfaction survey; Zhao et al. (2021) combined interviews with village cadres and planning experts to analyze the role of policy implementation in optimizing rural building space.

As an emerging data source, crowd-sourced geographic data provides a new perspective for the study of rural architectural spatial layout. Liu et al. (2019) used mobile phone signaling data to analyze the matching degree between rural residents' activity space and architectural layout; Yang et al. (2020) identified spatial activity hotspots in rural tourism areas based on social media check-in data; Zhang et al. (2022) combined volunteer geographic information (VGI) to build a spatial database of rural historical buildings.

Multi-Source Data Fusion Methods and Technologies

Multi-source data fusion refers to the integration and analysis of data from different sources, types and scales to obtain more comprehensive and accurate information (Zhang, 2010). In the study of rural building space layout, multi-source data fusion mainly involves key technologies such as data association, feature extraction, scale conversion and comprehensive modeling.

Data Association and Matching Technology

Data association is the basis of multi-source data fusion, which mainly solves the heterogeneity of different data sources in spatiotemporal reference systems, attribute structures and expressions. Liu et al. (2017) developed a multi-source data matching algorithm based on spatial location, realizing the spatial association of remote sensing images, land use data and statistical data; Wang et al. (2019) proposed a heterogeneous data association model based on semantic ontology to solve the semantic conflicts of data from different sources; Zhang et al. (2021) designed a multi-scale spatial unit conversion method to achieve unified expression of data with different spatial resolutions.

Feature Extraction and Recognition Technology

Feature extraction is an important step in obtaining key information about the spatial layout of rural buildings from multi-source data. Chen et al. (2018) combined deep learning methods to automatically extract rural building information from high-resolution remote sensing images; Li et al. (2020) applied object-oriented image analysis technology to identify the morphological characteristics and spatial organization patterns of rural buildings; Zhao et al. (2022) used spatiotemporal data mining methods to extract the spatial evolution characteristics of rural buildings from long-term remote sensing data.

Scale Conversion and Fusion Technology

Scale conversion is a key technology to solve the problem of inconsistent spatial and temporal scales of multi-source data. Yang et al. (2016) proposed a scale conversion method based on multi-resolution analysis to achieve the fusion of remote sensing data with different resolutions; Wang et al. (2019) used spatial interpolation and decomposition and reconstruction technology to solve the conversion problem between point scale and surface scale data; Song et al. (2021) developed a time series alignment algorithm to achieve unified processing of data with different time frequencies.

Comprehensive Modeling and Analysis Techniques

Comprehensive modeling is the core technology for analyzing the spatial layout of rural buildings based on the results of multi-source data fusion. Zhou et al. (2017) constructed a rural building spatial pattern analysis model integrating remote sensing, GIS and statistical data; Li et al. (2019) developed a multi-source data-driven rural building layout evaluation model based on machine learning; Hao et al. (2022) proposed a rural building spatial evolution prediction model combining knowledge graph and deep learning.

Case Studies	**Fusion data types**	**Fusion Method**	**Study Area**	**Key findings**	**References**
Identification and evolution analysis of rural building space pattern	Multi-temporal remote sensing images, DEM, statistical data	Object-based image analysis, statistical modeling	Yangtze River Delta, China	Reveals the "center-periphery" evolution pattern of rural architectural space pattern	Zhou et al., 2017
Analysis of driving forces of rural building space layout	Remote sensing data, socio-economic statistics, questionnaire surveys	Geographically weighted regression, structural equation modeling	Northeast China	Identified regional differences in factors affecting rural building layout	Li et al., 2019

Extraction of spatial morphological features of traditional villages	High-resolution images, historical maps, and field research	Deep learning, morphological analysis	Southwest China Mountain Area	Constructed a database of traditional village architectural space morphology characteristics	Yang et al., 2020
Evaluation of suitability of rural building space	GIS data, environmental monitoring, social surveys	Fuzzy comprehensive evaluation, spatial superposition analysis	North China Plain, China	Established a rural building space layout suitability zoning	Wang et al., 2021
Architectural space optimization under the background of rural revitalization	Remote sensing images, statistical data, policy texts	Cellular automata, scenario simulation	Beijing-Tianjin-Hebei Region, China	Proposed a spatial optimization model of "intensive and compact, multifunctional"	Zhang et al., 2022

Table 2: Typical Application Cases of Multi-Source Data Fusion in the Study of Rural Building Space Layout

Application of Multi-Source Data Fusion in Rural Building Spatial Layout Evaluation

Multi-source data fusion provides comprehensive data support and methodological techniques for the evaluation of rural building space layout, making the evaluation process more objective, comprehensive and accurate.

Construction of Evaluation Index System

Based on multi-source data fusion, researchers have constructed a multi-dimensional rural building space layout evaluation index system. Yang et al. (2018) constructed a rural building space morphology evaluation system including indicators such as morphological compactness, spatial continuity and boundary complexity based on remote sensing images and GIS data; Li et al. (2020) combined statistical data and questionnaire surveys to establish a comprehensive evaluation index of rural building space layout including three dimensions of economic benefits, social equity and ecological protection; Zhao et al. (2021) integrated multi-source geographic information data and developed a rural building space functional suitability evaluation index system.

Innovation of Evaluation Methods

Multi-source data fusion has promoted the innovation of rural building space layout evaluation methods. Chen et al. (2019) combined machine learning and spatial statistical methods to realize the automatic evaluation of rural building space layout based on multi-source data; Wang et al. (2020) applied big data mining technology to build a dynamic monitoring and evaluation system for rural building space layout; Song et al. (2022) developed an online evaluation tool for rural building space layout that supports multi-source data fusion based on a cloud computing platform.

Verification of Evaluation Results

Multi-source data fusion also provides a multi-reference for the verification of evaluation results. Liu et al. (2020) verified the rural building space evaluation results based on medium and low resolution remote sensing data by comparing high-resolution images with field survey data; Li et al. (2021) verified the accuracy of rural building space evolution simulation by comparing historical statistical data with model prediction results; Zhang et al. (2022) combined expert evaluation and resident satisfaction survey to verify the feasibility of rural building space layout optimization plan.

Optimal Decision-Making Framework for Rural Building Spatial Layout Based on Multi-Source Data Fusion

Theoretical Basis of the Decision-Making Framework

The rural building spatial layout optimization decision-making framework based on multi-source data fusion integrates the core ideas of system theory, multi-objective decision-making theory, spatial optimization theory and adaptive management theory (Long et al., 2018).

System theory emphasizes that the spatial layout of rural buildings is a complex system formed by the interaction of natural systems, social systems and economic systems. Optimization decisions need to comprehensively consider the interrelationships and evolution laws among the various elements of the system (Liu et al., 2018). Multi-objective decision-making theory provides theoretical tools for balancing multiple objectives such as ecological protection, economic development and social equity, and provides methodological support for solving the conflict of objectives in the optimization of rural building spatial layout (Zhou et al., 2019). Spatial optimization theory focuses on the spatial efficiency and balance of resource allocation, and provides theoretical guidance for the structural optimization and functional organization of rural building spatial layout (Wang et al., 2020). Adaptive management theory emphasizes decision-making flexibility and adaptability under uncertain conditions, and provides ideas for optimizing the spatial layout of rural buildings in a complex and changing environment (Zhang et al., 2021).

Basic Structure of the Decision-Making Framework

The rural building space layout optimization decision-making framework based on multi-source data fusion mainly includes four subsystems: data support system, evaluation and analysis system, optimization decision-making system and implementation monitoring system (Li et al., 2020).

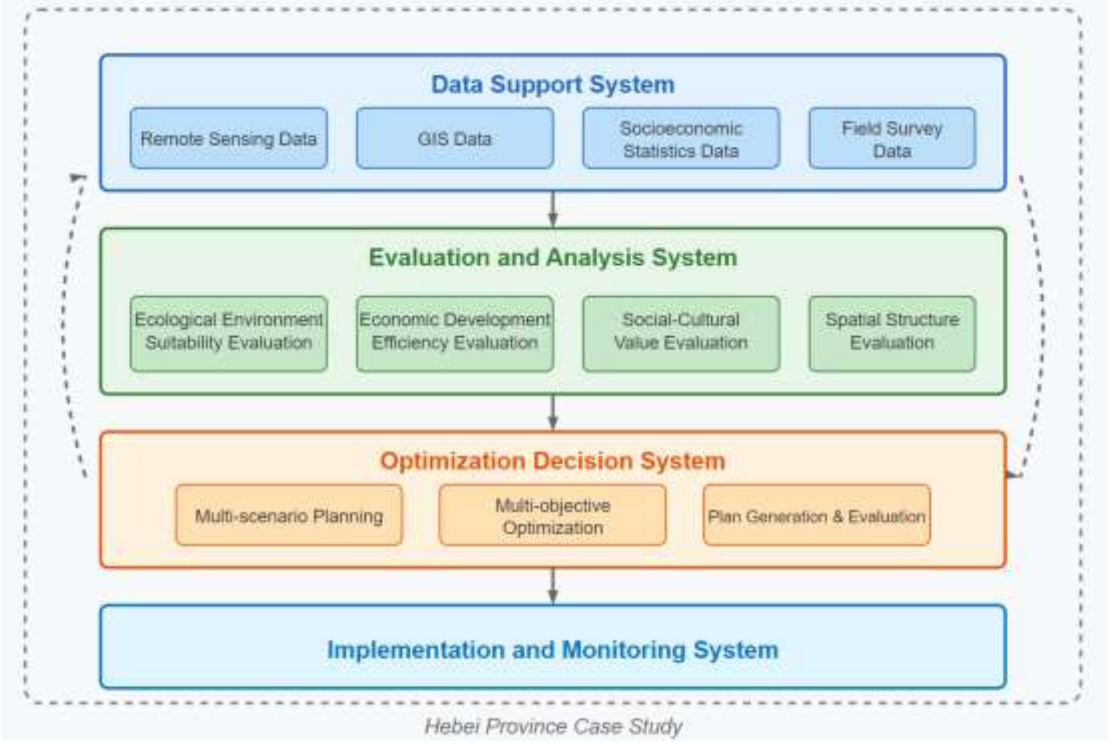

Fig. 1 Decision Framework for Optimizing Rural Building Space Layout Based on Multi-Source Data Fusion

The data support system is the basis of the decision-making framework and is responsible for the acquisition, processing and integration of multi-source data to build a comprehensive database of rural building space layout. The system transforms scattered and heterogeneous data into knowledge to support decision-making through data mining, knowledge discovery and information integration (Yang et al., 2019).

The evaluation and analysis system is the core of the decision-making framework, responsible for the evaluation of the current status of rural building space layout, problem diagnosis and influencing factor analysis. The system comprehensively evaluates the rationality and sustainability of rural building space layout by constructing a scientific and reasonable evaluation index system and evaluation method (Wang et al., 2021).

The optimization decision system is the key to the decision-making framework and is responsible for formulating the optimization goals, strategies and plans for the spatial layout of rural buildings. The system forms a scientific and reasonable decision-making plan through multi-objective planning, scenario simulation and plan evaluation (Zhang et al., 2022).

The implementation monitoring system is the guarantee of the decision-making framework and is responsible for the implementation, effect evaluation and dynamic adjustment of the optimization plan. The system ensures the effective implementation and continuous improvement of optimization decisions by establishing a long-term monitoring mechanism and feedback adjustment mechanism (Li et al., 2021).

Evaluation Index System Supported by Multi-source Data

Based on multi-source data fusion, the rural building space layout evaluation index system can be constructed from four dimensions: ecological environment, economic development, social culture, and spatial structure (Zhao et al., 2020).

Target layer	**Criteria Layer**	**Indicator layer**	**Data Source**	**Calculation method**
Comprehensive evaluation of rural building space layout	Ecological environment suitability	Terrain suitability	DEM data	Comprehensive evaluation of slope, aspect and elevation
		Disaster risk	Disaster history records, geological data	Analysis of multi-source disaster risk superposition
		Ecological sensitivity	Ecological functional zoning, remote sensing images	Ecological vulnerability and importance assessment
		Environmental Quality	Environmental monitoring data, remote sensing interpretation	Multi-factor comprehensive evaluation of environmental quality
	Economic development benefits	Intensive land use	Remote sensing images, land use data	Building density and floor area ratio analysis
		Industry support capabilities	Industrial statistics, spatial distribution of enterprises	Analysis of industry concentration and correlation
		Transportation accessibility	Road network data, public transportation information	Network analysis and reachability calculations
		Construction input-output ratio	Investment statistics, economic census data	Input-Output Analysis
	Social and cultural value	Historical and cultural preservation	Historical building survey and documentation	Evaluation of historical element preservation

		Community Identity	Questionnaires, social media texts	Social network analysis and text mining
		Landscape coordination	High-resolution images, on-the-ground photos	Landscape pattern index calculation
		Accessibility of public services	POI data and service facility distribution	Service facility coverage analysis
	Reasonable spatial structure	Space compactness	Building outline data, remote sensing images	Morphological index calculation
		Functional Mix	Building function survey, land use data	Functional Mixed Index Calculation
		Network connectivity	Road network, building distribution data	Space Syntax Analysis
		Spatial coordination	Multi-temporal remote sensing images and planning maps	Spatial conflict and coordination analysis

Table 3: Evaluation Index System of Rural Building Space Layout Based on Multi-Source Data Fusion

In terms of ecological environmental suitability evaluation, multi-source data fusion can provide more comprehensive environmental information. Liu et al. (2018) combined DEM data, meteorological data and soil data to construct an ecological suitability evaluation model for rural building layout; Wang et al. (2020) integrated remote sensing images and environmental monitoring data to analyze the spatial relationship between rural building layout and ecological environmental quality; Zhang et al. (2021) integrated historical disaster records and geological data to evaluate the disaster risk of rural building layout.

In terms of economic development benefit evaluation, multi-source data fusion helps to reveal the relationship between economic factors and spatial layout. Chen et al. (2019) combined remote sensing images and economic census data to analyze the correlation between rural building density and economic development level; Li et al. (2020) integrated transportation network data and industrial distribution data to evaluate the impact of transportation accessibility on rural building spatial layout; Zhao et al. (2022) combined investment statistics and land use change data to construct an economic benefit evaluation model for rural building layout.

In terms of social and cultural value evaluation, multi-source data fusion can capture richer social and cultural information. Yang et al. (2018) combined historical maps and field surveys to evaluate the cultural value of traditional village architectural layouts; Wang et al. (2021) integrated questionnaire surveys and social media data to analyze residents' satisfaction and recognition of rural architectural space layouts; Song et al. (2021) integrated POI data and population distribution data to evaluate the spatial fairness of rural public service facilities.

In terms of the evaluation of spatial structure rationality, multi-source data fusion provides a multi-scale and multi-dimensional spatial analysis method. Zhou et al. (2017) combined high-resolution images and building outline data to calculate the spatial compactness index of rural building layout; Li et al. (2019) integrated land use data and building function surveys to analyze the functional mix of rural buildings; Hao et al. (2021) integrated road network and building distribution data and applied space syntax theory to evaluate the network connectivity of rural building layout.

Optimal Decision-Making Method Under Multiple Scenarios

The optimization decision of rural building space layout based on multi-source data fusion needs to consider future uncertainties and multiple possible development paths, so multi-scenario analysis becomes an important decision-making method (Long et al., 2020).

Scenario Construction Method

Scenario construction is the basis of multi-scenario analysis, which mainly sets possible future development scenarios based on key driving factors and uncertainty analysis. Liu et al. (2019) identified key factors affecting the spatial layout of rural buildings in China, including urbanization process, industrial transformation, environmental policies and technological innovation, through the Delphi method and key uncertainty analysis; Zhang et al. (2020) combined expert evaluation and stakeholder participation to construct four typical development scenarios: ecological protection-led, economic growth-led, cultural heritage-led and comprehensive balance; Zhao et al. (2021) designed a variety of spatial development scenarios considering different intensities of regional coordinated development based on the actual situation in the Beijing-Tianjin-Hebei region.

Optimization Goals and Strategies

Different goals and strategies need to be set for the optimization of rural building space layout in different scenarios. Wang et al. (2021) proposed that in the scenario dominated by ecological protection, the optimization goal should emphasize the harmonious coexistence of building layout and natural environment, and adopt strategies such as ecological control line demarcation, building height limit control and ecological corridor protection; Li et al. (2020) suggested that in the scenario dominated by economic growth, the optimization goal should focus on spatial efficiency and industrial support, and promote strategies such as centralized building layout, mixed functional design and traffic-oriented development; Yang et al. (2021) pointed out that in the scenario dominated by cultural heritage, the optimization goal should highlight the protection of traditional spatial forms and cultural characteristics, and implement strategies such as historical style protection, cultural landscape restoration and characteristic style guidance; Song et al. (2022) believed that in the comprehensive balance scenario, the optimization goal should pursue multi-dimensional coordination of ecology, economy, culture and society, and adopt a flexible planning method adapted to local conditions.

Optimization Solution Generation and Evaluation

Based on multi-source data fusion, intelligent generation and scientific evaluation of optimization schemes under different scenarios can be achieved. Chen et al. (2020) developed a rural building space layout generation model based on deep learning, which can automatically generate multiple layout schemes according to different constraints; Wang et al. (2021) constructed a multi-criteria evaluation system to evaluate different optimization schemes from the dimensions of suitability, efficiency, fairness and feasibility; Zhang et al. (2022) applied participatory planning technology, combined with expert advice and residents' opinions, to conduct multiple rounds of optimization and adjustment of optimization schemes; Zhao et al. (2022) developed a GIS-based rural building space layout optimization decision support system, which realized the integrated processing of scheme generation, evaluation and visualization.

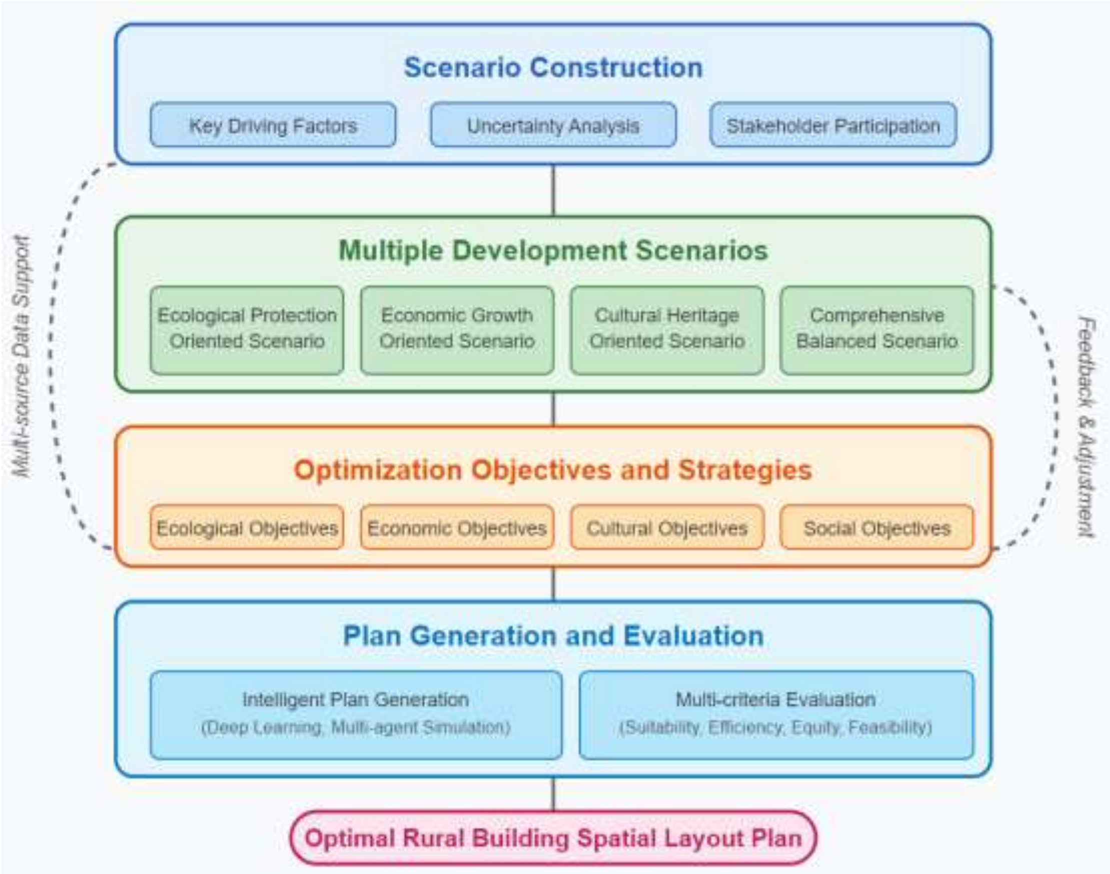

Figure 2 Optimal decision-making process for rural building space layout under multiple scenarios

Hebei Province Case Analysis

Characteristics of rural building space layout in Hebei Province

The spatial layout of rural buildings in Hebei Province shows obvious regional differences, which is closely related to its complex and diverse natural geographical conditions and level of socioeconomic development (Song et al., 2020).

Regional Differentiation Characteristics

Based on multi-source data analysis, the rural building space layout in Hebei Province can be divided into the following typical regional types:

(1) Plain agricultural area: mainly distributed in the North China Plain, including the plain areas of Shijiazhuang, Baoding, Cangzhou, Hengshui, etc. This area has flat terrain, fertile land,

developed agriculture, and the spatial layout of rural buildings presents a regular grid or cluster distribution, with a high building density and large village scale (Li et al., 2019).

(2) Mountainous agricultural areas: mainly distributed in the Taihang Mountains and Yanshan Mountains, including the mountainous parts of Zhangjiakou, Chengde, Baoding and Shijiazhuang. The terrain in this area is undulating, and rural buildings are mostly built on the mountain, distributed along contour lines or river valleys, in a belt-like or scattered pattern, with low building density and small village scale (Wang et al., 2020).

(3) Coastal agricultural areas: mainly distributed along the Bohai Bay, including the coastal areas of Tangshan, Qinhuangdao and Cangzhou. This area has both agricultural and fishery characteristics. Rural buildings are mostly distributed along the coastline in a strip or cluster shape, with a high degree of mixed building functions (Yang et al., 2021).

(4) Urban suburban rural areas: mainly distributed around large and medium-sized cities such as Shijiazhuang, Tangshan, and Baoding. This area is significantly affected by urban expansion, with rapid changes in the spatial layout of rural buildings, high building density, diversified functions, weakened traditional agricultural functions, and enhanced leisure tourism and commercial service functions (Zhao et al., 2021).

Spatiotemporal Evolution Characteristics

Through the analysis of multi-temporal remote sensing images and historical data, the evolution of rural building space layout in Hebei Province presents the following characteristics:

(1) Spatial expansion characteristics: From 1990 to 2020, the total amount of rural construction land in Hebei Province showed a trend of increasing first and then decreasing. It grew rapidly from 1990 to 2010, and the growth rate slowed down after 2010 and began to decrease locally. Spatial expansion mainly occurred along traffic arteries and around towns, showing a "point-axis" expansion model (Song et al., 2018).

(2) Structural reorganization characteristics: With the advancement of the rural revitalization strategy and new rural construction, the rural architectural space layout in Hebei Province has undergone significant structural reorganization, which is manifested in the merger and integration of small and scattered villages, the protection and renewal of traditional villages, and the planning and construction of characteristic villages (Li et al., 2020).

(3) Functional transformation characteristics: The functions of rural buildings in Hebei Province are showing a diversified development trend. The pure agricultural production function is weakened, and new functions such as leisure tourism, cultural experience, and creative industries are enhanced. The architectural form and spatial organization method are changing accordingly (Wang et al., 2021).

Region Type	**Building density (buildings/km^2)**	**Village size (household/village)**	**Spatial form**	**Features**	**Changing Trends**
Plain agricultural area	35-50	300-600	Grid-like, clumpy	Mainly agricultural production,	Intensification and scale

				with processing	
Mountainous agricultural areas	15-25	100-300	Band-shaped, scattered	Small-scale peasant economy and characteristic agriculture	Ecological protection, characteristic development
Coastal agricultural areas	25-40	200-400	Band-shaped, cluster-shaped	Combining agriculture and fisheries, developing tourism	Diverse functions and coastal features
Suburban agricultural areas	40-60	250-500	Clustered, diffuse	Urban agriculture, service industry development	Urban-rural integration, functional upgrade

Table 4 Comparison of Rural Building Space Layout Characteristics in Different Regions of Hebei Province

Evaluation of Rural Building Spatial Layout in Hebei Province Based on Multi-Source Data Fusion

Data Acquisition and Fusion

This study obtained multi-source data related to the spatial layout of rural buildings in Hebei Province, including Landsat series remote sensing images (1990-2020), Sentinel-2 high-resolution images (2015-2020), SRTM DEM data, 1:50000 basic geographic information data, Hebei Provincial Statistical Yearbook (2000-2020), the second national agricultural census data, Hebei Provincial Land Use Master Plan and rural planning documents, etc. (Li et al., 2021).

The data fusion process mainly adopts the following methods: (1) In the temporal dimension, remote sensing images and statistical data from different periods are integrated through time series analysis and change detection; (2) In the spatial dimension, the spatial reference systems of different data sources are unified through spatial matching and coordinate transformation; (3) In the attribute dimension, the association between spatial entities and attribute information is established through association analysis and feature extraction (Wang et al., 2021).

Evaluation Index Calculation

Based on the results of multi-source data fusion, the evaluation indexes of rural building space layout in Hebei Province were calculated. The calculation methods of some core indicators are as follows:

(1) Ecological environment suitability indicators:

- Terrain suitability: Based on DEM data, slope, aspect and elevation are calculated, and the terrain conditions for building layout are evaluated in combination with the suitability function (Liu et al., 2018).
- Ecological sensitivity: Based on ecological functional zoning and ecological red line data, the spatial relationship between building layout and ecologically sensitive areas is analyzed (Yang et al., 2020).

(2) Economic development benefit indicators:

- Intensive land use: Based on building outline data, building density and floor area ratio are calculated to evaluate land use efficiency (Chen et al., 2019).
- Traffic accessibility: Based on road network data, the time distance to major traffic arteries and nodes is calculated to analyze traffic convenience (Li et al., 2020).

(3) Social and cultural value indicators:

- Historical and cultural preservation: Based on historical building surveys and cultural relics census data, the preservation status of traditional buildings and historical elements is assessed (Wang et al., 2021).
- Public service accessibility: Based on POI data and public facility distribution, the coverage and accessibility of service facilities are calculated (Zhao et al., 2022).

(4) Spatial structure rationality index:

- Spatial compactness: Based on building distribution data, morphological indicators and spatial agglomeration are calculated to evaluate the compactness of the layout (Zhou et al., 2018).
- Functional mixture: Based on the land use and building function survey, the functional diversity index is calculated to analyze the functional mixture status (Song et al., 2021).

Analysis of Evaluation Results

The evaluation results based on multi-source data fusion show that there are significant regional differences and development imbalances in the spatial layout of rural buildings in Hebei Province (Li et al., 2021):

(1) Ecological and environmental suitability: The spatial layout of rural buildings in mountainous areas is well adapted to the natural environment, but there is a risk of disasters in local areas; rural buildings in plain areas occupy a large amount of arable land, which puts pressure on the agricultural production environment; the environmental quality in suburban areas of cities declines and the ecological space is squeezed (Wang et al., 2020).

(2) Economic development benefits: The economic benefits of urban suburbs and areas along transportation trunk lines are relatively high and their industrial support capacity is strong; the economic benefits of remote mountainous areas and poor areas are low and the level of intensive land use is insufficient; the development within the region is unbalanced and the efficiency of resource allocation needs to be improved (Zhang et al., 2021).

(3) Social and cultural values: The cultural value of traditional villages is not well preserved, and historical buildings and traditional patterns are disappearing at a fast rate; public service facilities are unevenly distributed, and the service level in mountainous and remote areas is low;

there is insufficient cultural integration between urban and rural areas, and there is a clear conflict between modern architecture and traditional style (Yang et al., 2022).

(4) Rationality of spatial structure: The overall spatial structure is scattered and the degree of intensiveness is not high; the functional mixing is insufficient and the production and living spaces are separated; there are differences in network connectivity and uneven transportation accessibility; spatial coordination needs to be improved and the connection with regional development strategies is insufficient (Zhao et al., 2022).

Optimization Strategy of Rural Building Space Layout in Hebei Province

Based on the multi-source data fusion evaluation results and multi-scenario analysis, differentiated optimization strategies for the spatial layout of rural buildings in different regions of Hebei Province can be proposed (Song et al., 2022).

Regional Differentiation Strategy

(1) Optimization strategy of building space in plain agricultural areas:

- Intensive layout strategy: Through village mergers and land consolidation, the centralized and compact layout of building space is promoted to improve land use efficiency (Chen et al., 2020).

- Functional composite strategy: Strengthen the composite functions of rural buildings, promote the organic integration of production, living and ecological functions, and enhance spatial vitality (Li et al., 2021).

- Pastoral landscape strategy: protect farmland landscape and rural style, create a "pastoral" spatial environment, and enhance the attractiveness of rural areas (Wang et al., 2022).

(2) Optimization strategies for building space in mountainous agricultural areas:

- Ecological adaptation strategy: Respect the natural terrain conditions, adopt a building layout that is coordinated with the mountain environment, and reduce interference with the ecological environment (Liu et al., 2020).

- Characteristic industry strategy: Combine characteristic agriculture and rural tourism development, optimize the architectural space layout, and form a "one village, one product" development model (Yang et al., 2021).

- Cultural protection strategy: protect the traditional village layout and historical buildings, inherit local cultural characteristics, and enhance cultural identity (Zhao et al., 2022).

(3) Optimization strategy of building space in coastal agricultural areas:

- Disaster prevention and mitigation strategies: Consider marine disaster risks, optimize building layout and structural design, and improve disaster resistance (Chen et al., 2019).

- Coastal characteristic strategy: highlight the coastal characteristics and shape the architectural style and spatial pattern with marine cultural characteristics (Li et al., 2020).

- Industrial integration strategy: Promote the integrated development of fisheries, agriculture and tourism, optimize the functional layout of buildings, and enhance industrial competitiveness (Wang et al., 2021).

(4) Optimization strategy for building space in rural areas near cities:

- Urban-rural integration strategy: Promote the two-way flow of urban and rural elements, optimize the architectural space layout of urban-rural fringe areas, and achieve complementary urban and rural functions (Zhang et al., 2020).
- Characteristic preservation strategy: preserve rural characteristics and agricultural landscapes, avoid the spread of urban homogeneity, and maintain rural uniqueness (Song et al., 2021).
- Service improvement strategy: Improve the layout of public service facilities, improve service levels and accessibility, and enhance regional attractiveness (Zhao et al., 2022).

Implementation Paths Under Multiple Scenarios

Based on the strategic background of coordinated development of Beijing-Tianjin-Hebei and rural revitalization, three main development scenarios can be constructed and corresponding implementation paths can be proposed (Li et al., 2022):

(1) Implementation path under the scenario dominated by ecological protection:

- Clarify ecological protection red lines and construction control zones, and strictly limit building development in ecologically sensitive areas.
- Promote the ecological transformation of rural buildings to improve energy efficiency and environmental friendliness.
- Construct ecological corridors and green networks to optimize the spatial relationship between buildings and the natural environment.
- Establish an ecological compensation mechanism to balance the relationship between ecological protection and economic development.

(2) Implementation path under the scenario dominated by industrial revitalization:

- Construct a spatial organizational model for the coordinated development of "industrial chain-value chain-space chain".
- Promote the integrated development of the primary, secondary and tertiary industries in rural areas and optimize the spatial layout of industrial functions.
- Improve rural infrastructure and public services, and enhance the attractiveness and livability of rural areas.
- Support rural innovation and entrepreneurship, cultivate new industries and new business models, and drive spatial reconstruction.

(3) Implementation path under the context of cultural heritage:

- Formulate protection and development plans for traditional villages, and systematically protect historical and cultural resources.
- Establish an architectural style guidance mechanism to shape an architectural style with local characteristics.
- Carry out transformation of rural public spaces and improve the quality and functions of cultural activity venues.

- Promote the integrated development of culture and tourism and activate the economic value of traditional cultural resources.

Policy Recommendations and Implementation Guarantees

In order to ensure the effective implementation of the optimization decision of rural building space layout, it is necessary to establish a sound policy support and implementation guarantee system (Zhao et al., 2022):

(1) Institutional innovation: Improve the rural land system and homestead management system, establish a market-oriented transfer mechanism for rural construction land, and activate the vitality of rural land elements (Wang et al., 2020).

(2) Technical support: Establish a rural building space layout monitoring and evaluation platform based on multi-source data fusion to provide technical support for decision-making (Li et al., 2021).

(3) Financial guarantee: Establish a diversified investment and financing mechanism to guide social capital to participate in the optimization of rural building space and solve the problem of capital shortage (Yang et al., 2022).

(4) Talent support: Cultivate professional talents familiar with rural planning and construction, and provide technical services and knowledge support (Song et al., 2021).

(5) Participation mechanism: Establish a villager participation mechanism, respect farmers' wishes and needs, and increase their recognition and participation in planning implementation (Zhang et al., 2022).

Conclusion and Outlook

Main Conclusions

This paper systematically reviews the research progress of rural building space layout optimization decision-making based on multi-source data fusion, and uses Hebei Province as a case study to draw the following main conclusions:

(1) Multi-source data fusion provides a new methodological framework and technical support for the study of rural building space layout. It can integrate remote sensing images, GIS data, statistical data, survey data, and multi-source geographic data to comprehensively analyze the spatial characteristics of rural buildings and their influencing factors.

(2) The rural building space layout evaluation system based on multi-source data fusion should be constructed from multiple dimensions such as ecological environmental suitability, economic development benefits, social and cultural values, and spatial structure rationality. Through scientific and reasonable indicator selection and evaluation methods, a comprehensive evaluation of rural building space layout can be achieved.

(3) Multi-scenario analysis is an effective decision-making method for dealing with future uncertainties. By constructing different development scenarios, setting differentiated optimization goals and strategies, and generating and evaluating multiple optimization schemes, it can provide scientific decision-making support for the optimization of rural building space layout.

(4) The spatial layout of rural buildings in Hebei Province shows obvious regional differences.

Plain agricultural areas, mountainous agricultural areas, coastal agricultural areas and urban suburban agricultural areas have different spatial characteristics and development problems, which require differentiated optimization strategies and implementation paths.

(5) The optimization of rural building space layout should be combined with regional development strategies and rural revitalization goals to build a spatial development model of "ecological livability, industrial prosperity, cultural heritage, and effective governance" to promote sustainable rural development.

Innovation and Shortcomings

The main innovations of this study are: (1) systematically sorting out the application methods and technical paths of multi-source data fusion in the study of rural building space layout; (2) constructing a rural building space layout evaluation index system and optimization decision-making framework based on multi-source data fusion; (3) proposing rural building space layout optimization strategies and implementation paths under multiple scenarios; (4) taking Hebei Province as an example, analyzing the optimization direction of rural building space layout under regional differences.

The shortcomings of the research are: (1) multi-source data fusion still faces technical challenges such as uneven data quality, inconsistent spatiotemporal scales, and complex fusion algorithms; (2) there is subjectivity in the determination of the weights of the evaluation index system and the selection of evaluation methods; (3) there is uncertainty in the scenario setting and future prediction of multi-scenario analysis; and (4) the data of the case analysis is limited and it is difficult to fully reflect regional differences.

Future Research Directions

Future research can be carried out in the following directions:

(1) Explore the application of big data and artificial intelligence technologies in the analysis of rural building spatial layout, and develop more efficient and intelligent data fusion algorithms and analysis methods.

(2) Strengthen the multi-scale and multi-temporal research on the evolution of rural building spatial layout, deeply analyze its driving mechanism and action path, and improve the accuracy of prediction and simulation.

(3) Improve the participatory decision-making mechanism for optimizing the spatial layout of rural buildings, integrate expert knowledge, residents' needs, and government intentions, and improve the scientific and democratic nature of decision-making.

(4) Strengthen the coordinated research on rural architectural spatial layout and rural industrial development, ecological protection, and cultural heritage, and explore multi-dimensional coordinated spatial optimization models.

(5) Carry out empirical research and demonstration projects on the optimization of rural building space layout, accumulate experience, and form optimization models and methods that can be extended and replicated.

(6) Explore the spatial organization model of smart villages under the background of "Internet +", and study the impact mechanism and response strategies of information technology on the spatial layout of rural buildings.

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