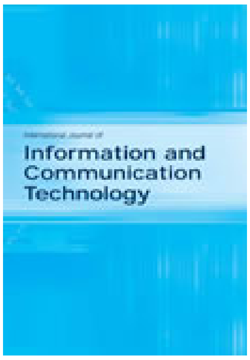

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Traditional settlement spatial landscape generation and optimisation using multidimensional GIS data driven method: a case study of Fujian province

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Traditional settlement spatial landscape generation and optimisation using multidimensional GIS data driven method: a case study of Fujian province

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Abstract: The digital analysis and generation optimisation of traditional settlement landscape spatial forms is an important issue in the field of urban and rural cultural heritage protection. This study focuses on typical traditional settlements in Fujian where diverse cultures blend together, and proposes a GIS-based multidimensional data-driven method for generating and optimising landscape spatial forms. A spatial form iterative optimisation algorithm that integrates parameterised generation and generative adversarial networks with multi-objective genetic algorithms is developed to achieve intelligent generation and dynamic optimisation of traditional settlement spatial forms. Empirical research has shown that this method can effectively analyse the three-dimensional spatial morphology characteristics of typical types such as Minnan Red Brick Cuo settlements and Minxi Tulou settlements. The research results have important practical value for the dynamic inheritance of cultural heritage under the background of rural revitalisation.

Keywords: geographic information system; generate adversarial networks; multi objective genetic algorithm; multidimensional data-driven approach; parameterised generation.

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1 Introduction

Traditional settlements, as spatial carriers formed by long-term interaction between humans and the natural environment, carry regional cultural genes and construction wisdom (Liu et al., 2023). In the process of rapid urbanisation, its landscape spatial form faces dual challenges of protection and development. Although there have been studies using GIS technology for settlement spatial analysis, they are mostly limited to single dimensional data or static descriptive research, lacking dynamic analysis of the multi-dimensional collaborative mechanism of 'natural environment built environment human environment', and even rarer is the data-driven spatial form generation and optimisation method system. This study takes the Fujian region as a typical example and proposes a GIS multidimensional data-driven framework for landscape spatial form generation, aiming to fill the methodological gap in the digital inheritance of traditional construction wisdom and the collaborative improvement of spatial efficiency.

In recent years, 3D GIS technology has significantly improved the quantitative analysis ability of settlement spatial morphology. In recent years, Liu et al. (2024) introduced a new framework that utilises cultural landscape gene theory to enhance the landscape spatial pattern of Linpu Village in China. Wang et al. (2023) integrated population, economy, and land dimensions based on multiple remote sensing images and socio-economic statistical data to construct a comprehensive urbanisation index, quantifying the spatiotemporal evolution patterns of NPP and urbanisation in Yunnan Province. The morphological gene theory proposed by Conzen (1960) laid the theoretical foundation for settlement spatial analysis. Turner (2007) introduced parametric methods to generate spatial forms that conform to historical context, but the lack of interpretability of the algorithm limits its practical application. Parametric design has made significant progress in the digital reconstruction of traditional buildings. Made contributions by comparing the computational modelling of morphogenesis in plant science with architectural design techniques. The 'digital humanities' approach advocated by Oxman (2008) emphasises embedding cultural semantics into generative algorithms, providing theoretical inspiration for multidimensional data-driven approaches.

This study innovatively integrates multidimensional GIS data with intelligent algorithms, breaking through the three limitations of existing research:

1 constructing a multidimensional database that includes terrain, architecture, streets, and cultural symbols, overcoming the shortcomings of a single data dimension

2 establish a synergistic model of natural environment constraints, built environment evolution, and human gene inheritance

3 develop a hybrid optimisation algorithm that embeds cultural semantics to achieve a dynamic balance between traditional gene inheritance and spatial efficiency improvement.

Taking typical settlements in southern and western Fujian as empirical objects, this study provides methodological innovation for cultural heritage protection from the perspective of digital humanities.

2 Relevant technologies

2.1 Geographic information system

GIS as the core technology system of spatial information science, is based on the cross integration of geography, surveying, computer science, and spatial statistics. Since the concept of ‘Canadian Geographic Information System’ was proposed, GIS has gradually evolved from a simple map digitisation tool to a comprehensive platform that integrates spatial data management, spatial analysis, and spatial decision support (Raihan, 2023). Its core theoretical framework is based on spatial cognitive models, emphasising the three-dimensional expression of geographic entity spatial location, attribute features, and temporal changes. Through the complementary application of vector data models and raster data models, it achieves multi-scale spatial representation from discrete point line surface elements to continuous field phenomena. The theoretical system of Geographic Information Science (GIScience) further establishes the position of spatial relationship reasoning, spatial heterogeneity analysis, and geographic visualisation principles as the fundamental theoretical pillars of GIS (Xia et al., 2022).

At the level of spatial analysis theory, GIS inherits and develops the traditional geographical location theory and spatial interaction model. The first law of geography proposed by US geographers, the law of spatial correlation decay with distance, laid the theoretical foundation for geographic statistical methods such as spatial autocorrelation analysis and kriging interpolation. The theory of spatial topological relationships strictly defines spatial relationships such as inclusion, intersection, and adjacency between geographic elements through the 9-intersection model, supporting core GIS operations such as overlay analysis and buffer analysis. The theory of geographic complexity breaks through the deterministic analysis framework of traditional GIS, introducing complex scientific methods such as fractal geometry and cellular automata into spatial simulation, providing theoretical tools for modelling dynamic processes such as urban expansion and land use change. In recent years, with the development of 3D GIS and spatiotemporal GIS, the ‘3D topological data model’ has solved the problem of expressing spatial relationships within building entities, while the ‘event driven spatiotemporal data model’ provides a temporal reasoning framework for analysing the evolution of historical settlement forms.

In terms of data modelling and processing theory, GIS has formed a unique spatial database theoretical system. The object relational spatial database theory achieves integrated management of spatial data and non-spatial attributes through the extension of SQL language. The theory of ‘spatial data cube’ introduces online analytical processing technology into the GIS field, supporting the aggregation analysis and data mining of multidimensional spatial data. In the data acquisition process, photogrammetric theory and remote sensing information extraction theory constitute important supports for GIS data sources, among which multispectral image classification algorithms and object-oriented image analysis methods significantly improve the accuracy of land use/cover classification. The theory of data uncertainty serves as the cornerstone of GIS quality control, and the error propagation model provides a reliability evaluation standard for multi-source data fusion (Berenbrok et al., 2022).

The theoretical integration of GIS and humanities and social sciences has given rise to a new paradigm of social geographic computing. The ‘space syntax’ theory reveals the interactive rules between social activities and spatial structure through topological network analysis, providing a quantitative tool for the study of traditional settlement street networks. The framework of ‘spatiotemporal behaviour analysis’ integrates GPS trajectory data and activity logs, deepening the spatiotemporal analysis of human environment interaction relationships. In the field of cultural heritage protection, the landscape archaeology information system theory emphasises the integration of historical maps, remote sensing images, and archaeological excavation data into a multi-layered spatiotemporal database, which resonates with the multidimensional data-driven approach proposed in this study. In recent years, the deep integration of machine learning theory and GIS has opened up new directions, such as the ‘GeoAI’ theory, which extracts spatial pattern features through deep learning algorithms and provides methodological support for the intelligent recognition of traditional settlement landscape genes (Narayanan and Manimaran, 2024).

The current development of GIS theory is undergoing a paradigm shift from ‘tool orientation’ to ‘intelligent services’. Volunteer geographic information theory has reconstructed the traditional spatial data production model; the theory of whole space information system is driving the technological innovation of three-dimensional solid modelling and integrated indoor and outdoor modelling. In the field of traditional settlement protection, these theoretical advances enable GIS not only to achieve accurate analysis of landscape spatial forms, but also to simulate the spatial effects of different protection strategies in digital twin environments through parametric modelling and multi-objective optimisation algorithms. The theory of digital twin cities integrates real-time sensor data with historical spatial databases, opening up new dimensions for the dynamic inheritance of cultural heritage. These theoretical achievements together form the academic foundation of this study, guiding the construction and practice of multidimensional data-driven methods (Supiyandi and Mailok, 2024).

2.2 Generative adversarial networks

GANs are unsupervised deep learning frameworks, whose core idea originates from the adversarial training mechanism in game theory. It achieves efficient modelling of complex data distributions through continuous adversarial games between generators and discriminators. In the field of digital generation of traditional settlement landscape spatial forms, GANs have become a key technology for solving the complexity of historical settlement forms and the problem of cultural gene inheritance due to their powerful nonlinear feature extraction ability and spatial pattern generation potential. The core task of a generator is to map random noise vectors into samples that conform to the true data distribution (Cai et al., 2021). Its essence is to construct a nonlinear transformation function from the hidden space to the target space through multi-layer neural networks; the discriminator acts as a binary classifier, using structures such as convolutional neural networks to probabilistically evaluate the authenticity of input samples. The two achieve synchronous optimisation through minimax game.

In traditional settlement generation scenarios, the hidden space vector of the generator is interpreted as the cultural gene encoding of settlement morphology, such as the proportion of swallowtail ridges in red brick houses in southern Fujian and the circular defence hierarchy of earthen buildings in western Fujian. The evaluation dimension of the discriminator integrates spatial syntactic indicators and cultural semantic features, forming a generation control mechanism that combines geometric accuracy and cultural rationality (Karras et al., 2021).

With the development of theory, conditional generative adversarial networks (CGAN) have significantly improved the controllability of the generation process by introducing auxiliary information as generation conditions. In traditional settlement generation, CGAN takes terrain elevation models, existing building texture features, and cultural symbol distributions as conditional inputs, enabling the generator to generate regional adaptation plans based on specific environmental constraints. For example, when inputting the defensive spatial pattern of the Earthen Building in Fujian Province settlement, the generator can independently extract key genes such as circular layout, watchtower density, and strengthen the expression of spatial defence logic through attention mechanism. This conditional generation not only avoids the limitations of explicit rule definitions in traditional parameterisation methods, but also captures the self-organising rules hidden in the construction of historical settlements. In addition, Wasserstein GAN solves the common problems of gradient vanishing and pattern collapse in original GAN training by using Earth Moore distance as the loss function (Gui et al., 2021). The theoretical innovation lies in transforming the adversarial target between the generator and discriminator into an optimal transmission problem between probability distributions, ensuring training stability through Lipschitz continuity constraints. This is particularly important for the generation of traditional settlements that require precise control of spatial form parameters such as courtyard height to width ratio and street curvature, as small parameter deviations may lead to distortion of cultural genes.

In the specific application of traditional settlement generation, GANs achieve multi-scale modelling of spatial morphology through a multi-level feature fusion mechanism. The network architecture of the generator usually adopts the U-Net structure, and its encoding decoding path can simultaneously capture local building details and global settlement patterns. In the encoding stage, low-level geometric features such as terrain contour lines and building contours are extracted through convolutional layers, while in the decoding stage, three-dimensional spatial forms with cultural semantics are gradually reconstructed through transposed convolution. The discriminator adopts the PatchGAN structure, which ensures the rationality of the generated scheme at micro scales such as street connectivity and building spacing through dense evaluation of local receptive fields (Kammoun et al., 2022). For example, in the generation of red brick houses in southern Fujian, the discriminator will jointly verify the accuracy of the brick and stone laying process of a single building and the overall feng shui layout logic of the settlement, avoiding the generation results that contradict cultural symbols and spatial logic.

The theoretical advantage of GANs in traditional settlement generation is also reflected in the cultural gene evolution mechanism hidden in their adversarial training process. The generator continuously adjusts network parameters to counteract pressure, essentially simulating the morphological adaptation process of historical settlements under natural environmental constraints and socio-cultural evolution (Brophy et al., 2023). This characteristic is highly consistent with the spatial evolution law of the earthen building in Fujian Province from Wufeng Building to Ring Building – the parameter update of generator is analogous to the intergenerational improvement of construction technology, and the evaluation criteria of discriminator corresponds to the screening pressure of regional cultural identity. Furthermore, by introducing cycle consistency loss and style transfer techniques, GANs can achieve innovative fusion of cross regional cultural features. For example, by interpolating the decorative elements of the red brick houses in southern Fujian with the defensive structure of the earthen buildings in western Fujian, a hybrid form that preserves traditional genes while adapting to modern functional needs is generated, providing a digital experimental platform for the dynamic inheritance of cultural heritage.

At the forefront of current research, GANs based on transformer architecture (such as StyleGAN3) enhance the modelling ability of long-range spatial dependencies through self attention mechanism, which is of great value for analysing the complex interaction between Feng Shui axis and natural terrain in traditional settlements. In addition, the fusion innovation of diffusion models and GANs achieves higher fidelity spatial morphology generation through a gradual denoising process, and its progressive generation characteristics are particularly suitable for traditional settlement scenes that require multi-level cultural gene collaborative expression. These theoretical advancements collectively promote the deep application of generative adversarial networks in the digital protection of cultural heritage, elevating it from a purely data-driven tool to a theoretical paradigm for intelligent reconstruction of cultural spaces (Dash et al., 2023).

2.3 Multi-objective genetic algorithm

Multi objective genetic algorithm (MOGA) is an important branch in the field of evolutionary computation. Its theoretical foundation is derived from Darwin's theory of evolution and swarm intelligence optimisation ideas, aiming to solve complex optimisation problems with multiple conflicting objective functions. Traditional single objective optimisation algorithms face fundamental limitations in cultural heritage protection scenarios. For example, improving the spatial efficiency of settlements often requires adjusting building density or street direction, but this may undermine the integrity of cultural genes. MOGA simulates the genetic, variation, and natural selection mechanisms of biological populations to find a Pareto optimal solution set that balances various objectives in the solution space, providing a mathematical framework for the 'protection development' trade-off in traditional settlement conservation. In the optimisation of traditional settlement space, the core value of MOGA lies in its ability to simultaneously address multiple objectives such as cultural gene inheritance, spatial functional adaptability, and ecological sustainability, and explore the optimal combination of morphological parameters through population evolution dynamics.

The theoretical breakthrough of NSGA-II algorithm is mainly reflected in three aspects: firstly, the introduction of a fast non-dominated sorting strategy, which stratifies individuals in the population according to dominance relationships, and defines the dominance level (front) as the preliminary criterion for individual superiority and inferiority, ensuring that the algorithm prioritises retaining high-quality solutions; secondly, the concept of crowding distance is proposed, which quantifies the distribution density of the solution set by calculating the Euclidean distance between individuals and adjacent solutions in the target space, in order to maintain population diversity; finally, an elite retention strategy is adopted to merge the parent and offspring populations and perform non-dominated sorting and crowding screening to avoid the loss of high-quality genes during the evolution process. In traditional settlement optimisation scenarios, each individual corresponds to a spatial form scheme, and its chromosome encoding usually includes parameters such as building density, courtyard height to width ratio, and street curvature. The fitness function needs to integrate cultural gene similarity measures (such as morphological matching algorithms), spatial efficiency indicators (such as street accessibility, building lighting coefficient), and ecological constraints (such as terrain fitness), and calculate the objective function value in real-time through GIS spatial analysis engines. For example, the optimisation of the earthen building in Fujian Province needs to balance the defence performance (the watchtower coverage is quantified through the horizon analysis) and the residential comfort (the ventilation efficiency is evaluated through CFD simulation). NSGA-II automatically identifies the solution sets that meet both conditions through non-dominated sorting, and then selects the most representative optimisation scheme according to the congestion degree (Li et al., 2021).

In the specific implementation of optimising the spatial form of traditional settlements, MOGA demonstrates unique theoretical advantages. Firstly, the parameter encoding strategy deconstructs complex spatial forms into heritable gene sequences, such as decomposing the overall layout of a settlement into discrete parameters such as building base polygon vertex coordinates, roof form codes, street and alley connection topologies, making morphological variations controllable while maintaining the continuity of cultural genes. Secondly, the design of crossover and mutation operators needs to incorporate domain knowledge, such as using cultural crossover based on cultural genetic similarity, which only exchanges gene fragments between individuals with the same building type to avoid generating cultural distortion schemes that mix Minnan red brick houses and earthen buildings. The mutation operation introduces a mixture mechanism of Gaussian perturbation and Cauchy perturbation. The former is used to fine tune building size parameters, while the latter promotes leapfrog innovation in the topology structure of street and alley networks. Thirdly, the constraint handling mechanism ensures that the optimisation scheme meets hard constraints, such as the red line of cultural relics protection scope and building height limit, through penalty function method or feasible solution priority strategy. These theoretical innovations enable MOGA to effectively coordinate the contradictory relationship between ‘rigid constraints’ and ‘elastic innovation’ in the protection of historical settlements.

In recent years, the theoretical development of MOGA has shown two major trends: on the one hand, the NSGA-III algorithm based on reference points significantly improves the optimisation efficiency of high-dimensional objectives (such as optimising more than ten spatial indicators at the same time) by introducing a reference point set to partition the target space, which is particularly important for settlement renewal projects that need to coordinate multidimensional objectives such as cultural heritage, ecology, and economy; on the other hand, the integration of hybrid proxy models (such as kriging models and radial basis function networks) with MOGA significantly reduces the number of computationally expensive GIS spatial analyses by constructing an approximate substitute model for the objective function. In addition, the introduction of dynamic multi objective optimisation theory (DMOEA) enables algorithms to adapt to the temporal changes in settlement protection needs, such as embedding typhoon disaster risk prediction models into objective functions, automatically adjusting the wind resistance performance weights of spatial forms, and achieving adaptive optimisation.

In the field of digital protection of cultural heritage, the collaborative application of MOGA and generative adversarial networks has created a new paradigm of ‘generation optimisation’ closed-loop. The candidate solutions output by the generator network serve as the initial population of MOGA, and the Pareto frontier solution set is selected through multi-objective evolution (Taherzadeh-Shalmaei et al., 2023). These high-quality solutions then feed back into the training data of the generator, forming a spiral optimisation loop. The theoretical value of this hybrid architecture lies in the fact that the generator breaks through the design space limitations of traditional parametric methods and explores potential combinations of cultural genes; MOGA, on the other hand, uses a multi criteria screening mechanism to ensure that the generated solutions strike a balance between traditional continuity and functional innovation. For example, in the generation of circular defence structure of the earthen building in Fujian Province, the generator may propose a radical scheme to add a peripheral moat, and MOGA will revise it as a compromise scheme to locally deepen the existing drainage ditch through the trade-off analysis of defence effectiveness and construction cost. This theoretical fusion not only enhances the global search capability of spatial form optimisation, but also endows the cultural heritage protection process with dynamic adaptability, providing intelligent decision support for the dynamic inheritance of traditional settlements in the context of rural revitalisation.

3 Traditional settlement landscape spatial form generation and optimisation method driven by GIS multidimensional data

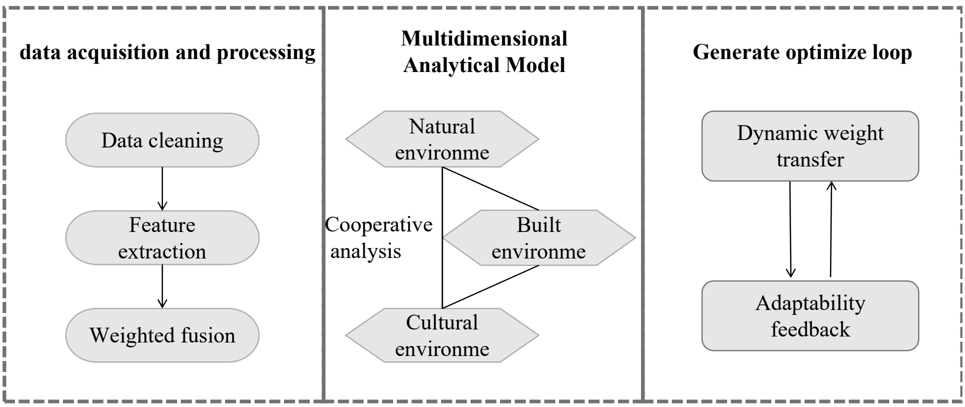
This study is based on the GIS multidimensional data-driven framework to construct a full process method system for generating and optimising the spatial form of traditional settlement landscapes. The method framework is shown in Figure 1.

Firstly, high-precision point cloud data (spatial resolution $\leq$ 5 cm) of typical settlements in Fujian were obtained through drone oblique photography and ground 3D laser scanning. Cultural gene features were extracted by combining historical literature and field investigations, and a multidimensional spatial database was constructed that integrates terrain elevation model, building vector polygon (building footprint), street topology network (space syntax graph), and cultural gene coding (cultural gene matrix). The data fusion adopts a weighted superposition model:

$$D_{\text{integrated}} = \sum_{i=1}^{n} w_i \cdot L_i \otimes M_i \quad (1)$$

where L_i represents the i^{th} layer data (such as terrain, buildings, streets, etc.), M_i is the semantic mask matrix of the corresponding layer, w_i is the hierarchical weight calculated based on entropy weight method, and ⊗ represents spatial convolution operation, used to eliminate data scale differences.

Figure 1 Method framework diagram



The landscape gene recognition module introduces an improved morphological matching algorithm and defines a cultural gene similarity measurement function:

$$S(G_p, G_r) = \frac{1}{N} \sum_{k=1}^{N} \exp\left(-\frac{\left\| f_k(p) - f_k(r) \right\|^2}{2\sigma^2} \right) \quad (2)$$

where G_p represents the gene of the tested settlement, G_r represents the reference gene template, f_k represents the k^{th} morphological feature (such as roof curvature and wall decoration complexity), and σ represents the Gaussian kernel bandwidth parameter. By setting a threshold, cultural gene units with significant regional characteristics can be screened out.

The spatial form generation module adopts the conditional generative adversarial network architecture, and the loss function of its generator G is defined as:

$$L_G = E_{z \sim p_z, c \sim p_c} \left[\log(1 - D(G(z \mid c), c) \right] + \lambda \cdot TV(G(z \mid c)) \quad (3)$$

The loss function of discriminator D is:

$$L_D = -E_{x \sim p_{data}} [\log D(x \mid c)] - E_{z \sim p_z} [\log(1 - D(G(z \mid c) \mid c))] \quad (4)$$

where the condition vector c contains constraint information such as terrain slope and existing building density. TV is the total variation regularisation term used to smooth the geometric transition of the generated shape, and λ is the trade-off coefficient. The generator adopts the U-Net structure, which includes eight layers of convolution and skip connections. The discriminator uses the PatchGAN architecture to evaluate the local rationality of spatial morphology through local receptive fields (64 × 64 pixels).

The multi-objective optimisation module is based on the NSGA-II algorithm and defines a dual objective function:

$$f_1 = 1 - S\left(G_{new}, G_{historic}\right) \tag{5}$$

$$f_2 = \sum_{j=1}^{m} \alpha_j \cdot \left(1 - \frac{Q_j^{new}}{Q_j^{\max}}\right) \tag{6}$$

where f_1 represents the loss of cultural gene inheritance, f_2 is the comprehensive loss of spatial efficiency, Q_j includes indicators such as street and alley integration (calculated through spatial syntax), building lighting coefficient (based on sunshine simulation), and public space coverage, and α_j is the indicator weight determined by entropy weight method. In the initialisation stage of the population, non-dominated solutions are selected from the 1,000 candidate schemes generated by CGAN as the initial population. Individual encoding is based on real numbers, with a chromosome length of 28 dimensions, corresponding to parameters such as building density, courtyard height to width ratio, and street curvature.

The crossover and mutation operations are designed as adaptive strategies: the crossover probability p_c dynamically adjusts with the evolution algebra t:

$$p_c(t) = 0.9 - 0.5 \cdot \frac{t}{T_{\max}} \tag{7}$$

The mutation probability p_m is set based on the individual crowding degree d_i:

$$p_m(i) = 0.1 + 0.4 \cdot \frac{d_i - d_{\min}}{d_{\max} - d_{\min}} \tag{8}$$

This mechanism encourages global exploration in the early stages of evolution and focuses on local optimisation in the later stages (Xue et al., 2021). During the fitness assessment phase, the GIS spatial analysis engine calculates the values of each objective function in real-time, with a single iteration time controlled within 120 seconds.

The dynamic weight transfer learning module adopts a feature pyramid structure to transfer the defence gene features of the Minxi Tulou (extracted through pre trained VGG16 network) to the task of generating red brick houses in Minnan:

$$L_{transfer} = \beta \cdot \left\| \phi_s(G(z|c)) - \phi_t(G(z|c)) \right\|_2^2 \tag{9}$$

where ϕ_s and ϕ_t represent the feature extraction functions of the source domain (Tulou) and the target domain (Hongbrick Cuo), respectively, and β is the transfer intensity coefficient. Finally, through the comprehensive decision-making of Pareto front solution set screening and expert evaluation system (AHP analytic hierarchy process), the optimal spatial form scheme is output.

4 Experimental results and analysis

This study takes typical traditional settlements in the two cultural regions of southern Fujian and western Fujian as experimental objects to systematically verify the effectiveness of the proposed method. Selecting the Minnan Red Brick Cuo settlement and the Minxi Tulou settlement as core cases, this study focuses on examining the accuracy of spatial form generation, multi-objective optimisation efficiency, and cultural gene inheritance effects driven by multidimensional data. A digital experimental environment with full coverage and multi-source fusion has been constructed.

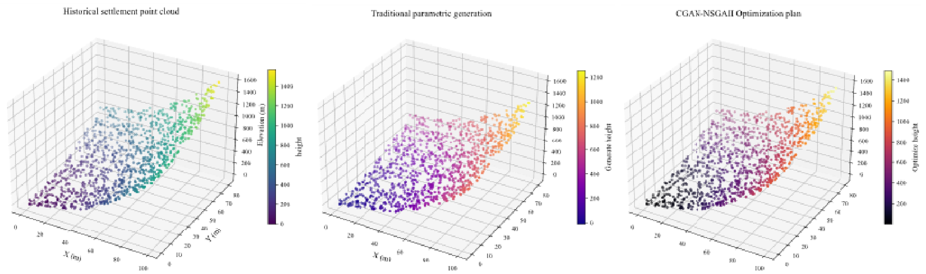
4.1 Experimental data and preprocessing

Geospatial data is obtained through the collaboration of drone oblique photography and ground 3D laser scanning. Using the DJI M300 drone equipped with a P1 lens (35 mm full frame sensor), a 0.5 cm resolution image of Wulin Village was collected at a height of 80 metres and an overlap rate of 80% (covering an area of 3.2 km^2). The core area buildings were supplemented with millimetre level point cloud data using the FARO Focus S350 3D laser scanner (accuracy ± 1 mm, single station scanning time 4 minutes). The raw data is encrypted and densely matched using ContextCapture to generate a 5 cm accurate 3D model of the real scene. The terrain DEM (grid size 5 m), building vector boundaries (300 red brick houses, 50 earthen buildings), and street topology network (1,235 nodes, connectivity 1.8–4.2) are further extracted. Extract 16 typical genetic features from cultural gene data, including the ‘brick in stone’ masonry technique for red brick houses and the ‘three halls and two horizontal’ spatial sequence for earthen buildings, encoded as a 28 dimensional feature vector. The collection of environmental parameters includes microclimate data (wind speed, temperature and humidity, sunshine hours) and soundscape data (festive gong and drum sound sample frequency 50–5,000 Hz), which are continuously collected for 72 hours through a wireless sensor network (10 monitoring points) as physical constraints for spatial form optimisation.

4.2 Space form generation experiment

To verify the morphological modelling ability of CGAN, a comparative experiment was designed: the terrain slope and existing building density of Wulin Village were input as condition vectors, and traditional parameterisation methods (rhino + grasshopper rule system) were used to generate ten candidate schemes with the CGAN model proposed in this paper. As shown in Figure 2 (left: historical settlement point cloud; middle: traditional parameterised generation; right: CGAN-NSGAII optimisation scheme), the traditional method relies on explicit rule constraints, resulting in a deviation of courtyard height to width ratio from historical values, and the complexity of swallowtail ridge decoration is only 72.3% of historical samples. The CGAN generation scheme, through the cultural gene reinforcement mechanism in adversarial training, stabilises the courtyard aspect ratio within a reasonable range of 1:1.7–1.9, and improves the matching degree of the swallowtail spine gene to 87.4%. Further analysis of the street and alley network topology showed that the integration degree of the optimisation plan increased from 0.52 to 0.63, and the Pearson correlation coefficient between its spatial syntax curve and historical settlements reached 0.91 ($p < 0.01$), indicating that the generative model effectively inherited the spatial organisation logic of traditional construction.

Figure 2 Comparison of the generation results of red brick houses in southern Fujian (see online version for colours)



4.3 Multi objective optimisation process analysis

In the optimisation experiment of tulou in western Fujian, the dual optimisation objectives were set as the defence effectiveness index (the coverage rate of the watchtower was calculated through visual field analysis) and the living comfort index. As shown in Figure 3, after 200 generations of evolution using the NSGA-II algorithm, the Pareto front of the initial population shows a significant rightward shift trend. When the defence effectiveness increases from 0.68 to 0.83, the living comfort remains ≥ 0.75 (ventilation efficiency ≥ 0.82). The evolution of key parameters shows that the thickness of the outer protective wall gradually converges from 1.2 m to 1.5 m, and the proportion of internal courtyard area remains stable at 28–31%, verifying the cultural adaptability of the algorithm in parameter search. It is worth noting that during the evolution process, there have been several 'outlier solutions' with high defence effectiveness but low comfort. After analysis, it was found that these solutions excessively increase the thickness of the protective wall (>1.8 m), resulting in obstruction of the internal ventilation path. The algorithm uses a crowding distance filtering mechanism to ultimately retain an equilibrium solution with a defence effectiveness of 0.79 and a comfort level of 0.81, resulting in a comprehensive improvement of 6.7% compared to the historical average.

4.4 Verification of cultural gene inheritance degree

Quantitatively evaluate the cultural gene inheritance effect of the generated scheme through morphological matching algorithm. Figure 4 shows that the gene intensity of the 'white stone pedestal' in the red brick house increased from 0.79 to 0.86, and its spatial distribution entropy decreased by 15.3%, indicating that the optimised scheme more concentrated on reproducing the core area of traditional masonry techniques. The gene distribution entropy of the 'circular defence hierarchy' in Tulou decreased by 12.7%, and the standard deviation of the distance between watchtowers decreased from 8.2 m to 5.7 m, approaching the regular layout of historical settlements (4.9 m). The analysis of soundscape genes showed that the correlation coefficient between the sound pressure level distribution of the festival activity space in the optimised plan and historical samples was $r = 0.91$, and the peak error of the main frequency was ≤ 3 dB (A), verifying the synergistic protection effect of spatial form and intangible cultural elements.

Figure 3 Fujian western tulou optimisation Pareto frontier (see online version for colours)

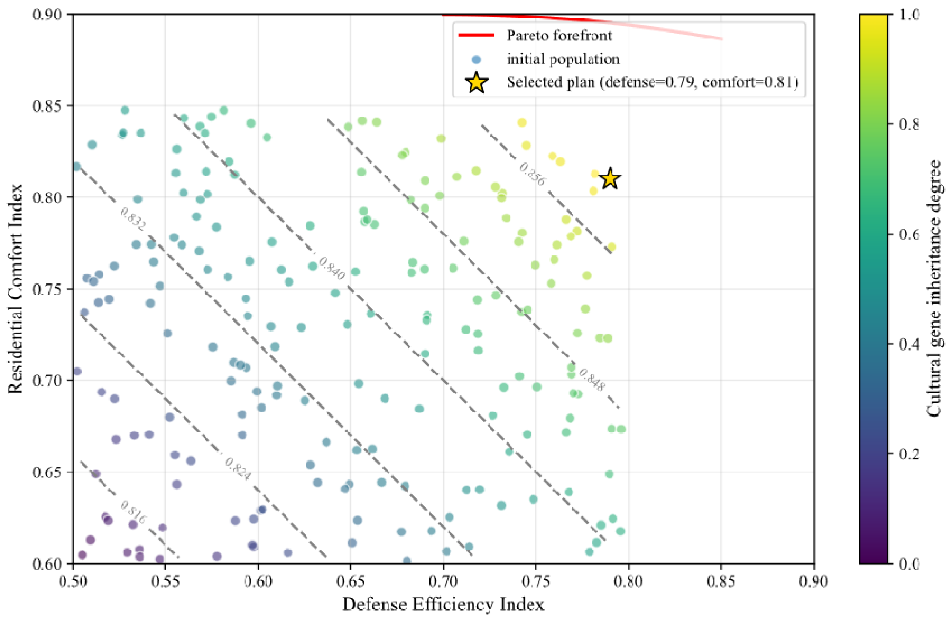
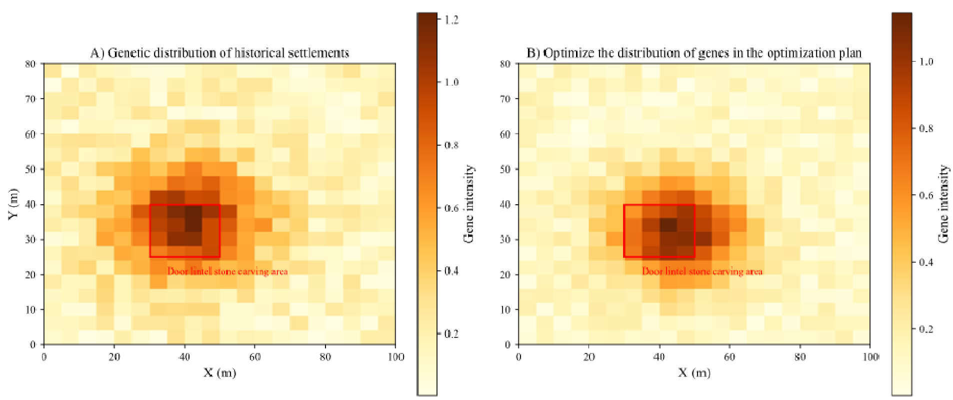


Figure 4 Comparison of cultural gene heat maps (see online version for colours)



4.5 *Comprehensive performance evaluation*

Table 1 compares the performance of traditional parameterisation methods and the method proposed in this paper in key indicators: the degree of cultural gene inheritance has increased from 73.2% to 85.7%, the integration of streets and alleys has increased by 18.9%, and the optimisation of building lighting coefficient has reached 16.9%. In terms of algorithm efficiency, the optimisation time for a single scheme has been reduced from 42 minutes to 28 minutes, mainly due to the parallel generation capability of CGAN and the elite retention strategy of NSGA-II. The microclimate simulation results show that the optimised summer average wind speed in Wulin Village has increased by 0.4 m/s, which is highly consistent with the ecological wisdom of ‘wind guidance and cooling’ in historical construction. In the case of Tianluokeng Tulou, the optimisation plan delayed the peak surface runoff during the rainy season by 12 minutes and reduced the runoff coefficient by 9.3%, reflecting the innovative integration of traditional wisdom and modern hydrological models.

Table 1 Industrial robot sorting control task list

Index	*Traditional parameterisation methods*	*CGAN-NSGAII*
Cultural gene inheritance degree	73.2%	85.7%
Integration degree of streets and alleys	0.58	0.69
Building lighting coefficient	0.71	0.83
Defence efficiency index	0.75	0.79
Residential comfort index	0.78	0.81
Single solution optimisation time (minutes)	42	28
Diversity of spatial forms (Shannon entropy)	0.65	0.82

5 Conclusions

This study takes traditional settlements in Fujian as the research object, and proposes a GIS-based multi-dimensional data-driven method system for landscape spatial form generation and optimisation to address the collaborative challenges of cultural gene inheritance and modern functional enhancement in cultural heritage protection. By integrating geographic spatial data, cultural gene features, and environmental parameters, a multi-dimensional collaborative analysis model of natural environment built environment human environment was constructed. The GANs were innovatively combined with NSGA-II to achieve intelligent generation and dynamic optimisation of traditional settlement spatial forms.

At the theoretical level, research has broken through the limitations of single dimensional GIS analysis, proposed a morphological quantification model of cultural genes and a spatial syntactic fusion mechanism, and constructed a settlement morphology coding system containing 28 dimensional control parameters. Through adversarial training with CGAN, the model is able to autonomously extract deep spatial features such as the swallowtail ridge decoration pattern of red brick houses in southern Fujian and the circular defence logic of earthen buildings in western Fujian. In terms of multi-objective optimisation, an improved NSGA-II algorithm is introduced to maintain a balanced development between defence effectiveness and residential comfort through non-dominated sorting and dynamic weight transfer strategies.

This study provides three contributions to the digital protection of traditional settlements: in terms of methodology, it establishes a full chain technical framework of data collection gene analysis intelligent generation multi-objective optimisation; on a practical level, the GIS intelligent algorithm collaborative platform developed can support dynamic evaluation and decision-making of protection schemes; in terms of theoretical value, it reveals the inherent mechanism of cultural gene driven spatial form evolution, providing a new paradigm for the dynamic inheritance of cultural heritage under the background of rural revitalisation.

Declarations

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All authors declare that they have no conflicts of interest.

References

Berenbrok, L.A., Tang, S., Gabriel, N., Guo, J., Sharareh, N., Patel, N., Dickson, S. and Hernandez, I. (2022) 'Access to community pharmacies: a nationwide geographic information systems cross-sectional analysis', *Journal of the American Pharmacists Association*, Vol. 62, No. 6, pp.1816–1822.

Brophy, E., Wang, Z., She, Q. and Ward, T. (2023) 'Generative adversarial networks in time series: a systematic literature review', *ACM Computing Surveys*, Vol. 55, No. 10, pp.1–31.

Cai, Z., Xiong, Z., Xu, H., Wang, P., Li, W. and Pan, Y. (2021) 'Generative adversarial networks: a survey toward private and secure applications', *ACM Computing Surveys (CSUR)*, Vol. 54, No. 6, pp.1–38.

Conzen, M.R.G. (1960) 'Alnwick, Northumberland: a study in town-plan analysis', *Transactions and Papers (Institute of British Geographers)*, Vol. 27, No. 5, pp.111–122.

Dash, A., Ye, J. and Wang, G. (2023) 'A review of generative adversarial networks (GANs) and its applications in a wide variety of disciplines: from medical to remote sensing', *IEEE Access*, Vol. 12, No. 3, pp.18330–18357.

Gui, J., Sun, Z., Wen, Y., Tao, D. and Ye, J. (2021) 'A review on generative adversarial networks: algorithms, theory, and applications', *IEEE Transactions on Knowledge and Data Engineering*, Vol. 35, No. 4, pp.3313–3332.

Kammoun, A., Slama, R., Tabia, H., Ouni, T. and Abid, M. (2022) 'Generative adversarial networks for face generation: a survey', *ACM Computing Surveys*, Vol. 55, No. 5, pp.1–37.

Karras, T., Aittala, M., Laine, S., Härkönen, E., Hellsten, J., Lehtinen, J. and Aila, T. (2021) 'Alias-free generative adversarial networks', *Advances in Neural Information Processing Systems*, Vol. 34, No. 2, pp.852–863.

Li, H., Xu, B., Lu, G., Du, C. and Huang, N. (2021) 'Multi-objective optimization of PEM fuel cell by coupled significant variables recognition, surrogate models and a multi-objective genetic algorithm', *Energy Conversion and Management*, Vol. 236, No. 8, p.114063.

Liu, P., Zeng, C. and Liu, R. (2023) 'Environmental adaptation of traditional Chinese settlement patterns and its landscape gene mapping', *Habitat International*, Vol. 135, No. 12, p.102808.

Liu, S., Wu, L., Xiang, C. and Dai, W. (2024) 'Revitalizing rural landscapes: applying cultural landscape gene theory for sustainable spatial planning in Linpu Village', *Buildings*, Vol. 14, No. 8, p.2396.

Narayanan, K.J.S. and Manimaran, A. (2024) 'Recent developments in geographic information systems across different application domains: a review', *Knowledge and Information Systems*, Vol. 66, No. 3, pp.1523–1547.

Oxman, R. (2008) ‘Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium’, *Design Studies*, Vol. 29, No. 2, pp.99–120.

Raihan, A. (2023) ‘A comprehensive review of the recent advancement in integrating deep learning with geographic information systems’, *Research Briefs on Information and Communication Technology Evolution*, Vol. 9, No. 14, pp.98–115.

Supiyandi, S. and Mailok, R.B. (2024) ‘Application of geographic information systems in sustainable development initiatives’, *Prosiding Universitas Dharmawangsa*, Vol. 4, No. 1, pp.410–415.

Taherzadeh-Shalmaei, N., Rafiee, M., Kaab, A., Khanali, M., Rad, M.A.V. and Kasaeian, A. (2023) ‘Energy audit and management of environmental GHG emissions based on multi-objective genetic algorithm and data envelopment analysis: an agriculture case’, *Energy Reports*, Vol. 10, No. 4, pp.1507–1520.

Turner, A. (2007) ‘From axial to road-centre lines: a new representation for space syntax and a new model of route choice for transport network analysis’, *Environment and Planning B: Planning and Design*, Vol. 34, No. 3, pp.539–555.

Wang, S., Wei, G., Gao, M. and Fan, Y. (2023) ‘Investigating the mechanism of urbanization on the net primary productivity of vegetation in the Yangtze River Economic Belt: a comprehensive analysis from global and local effects’, *Frontiers in Ecology and Evolution*, Vol. 11, No. 1, p.1231487.

Xia, H., Liu, Z., Efremochkina, M., Liu, X. and Lin, C. (2022) ‘Study on city digital twin technologies for sustainable smart city design: a review and bibliometric analysis of geographic information system and building information modeling integration’, *Sustainable Cities and Society*, Vol. 84, No. 6, p.104009.