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Adaptability assessment of the Enning road heritage district in China based on GA-BP neural network

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In complex urban systems, heritage districts must adapt beyond their original functions, requiring innovative reuse strategies to meet urban development demands. This study integrates socio-cultural and qualitative factors to enhance adaptive reuse predictions while fostering inclusive, community-driven renewal. Using a GA-BP neural network model, stakeholder mapping, and focus group interviews, the findings highlight two key aspects: (1) cultural significance, per capita consumption, and functional type serve as critical indicators for sustainable adaptive reuse, and (2) participatory governance and transparent decision-making are essential for effective implementation, with professional mediators and targeted support aiding conflict resolution. The governance transformation of Enning Road exemplifies a multi-network approach that integrates government leadership, enterprise-driven operations, multi-stakeholder participation, and benefit-sharing mechanisms. These insights contribute to the sustainable revitalization of heritage districts, offering a replicable model for balancing heritage preservation with urban development.

Keywords Adaptive reuse, Heritage district, GA-BP neural networks, Multi-stakeholder negotiations, Regeneration

The revitalization of heritage district (HD) presents a complex challenge, demanding the integration of adaptive reuse, preservation, and enhancement of tourist satisfaction as key measures of success[1]. HDs, defined as urban areas designated for heritage protection and adaptive reuse, involves more than the repurposing of individual buildings. The process also encompasses the renewal and transformation of public spaces, which play a crucial role in fostering community engagement, cultural vibrancy, and economic sustainability. This study examines both the reuse of heritage buildings and the renewal of public spaces within HDs, focusing on how these elements work together to create a dynamic, sustainable environment.

Unlike smaller architectural ensembles, HDs specifically refer to areas where heritage protection and adaptive reuse are central to the urban planning strategy[2]. The designation of HDs is regulated by national and municipal policies that aim to balance the need for preservation with the demands of urban development. This study aligns with Chinese conservation policies by adopting the term 'heritage district' to ensure clarity in discussions on heritage management and urban regeneration[3].

Since the 1950s, urban redevelopment in western countries has frequently displaced lower-income residents, as initial efforts prioritized short-term reconstruction and economic gains over long-term community cohesion[4–6]. However, by the 1980s, a paradigm shifts towards regeneration strategies emerged, which emphasized social development, cultural preservation, and governance as integral components of urban renewal. Adaptive reuse, which retrofits heritage buildings for new functions while retaining their historical significance, has become a key mechanism in the sustainable transformation of HDs[7,8]. In many countries, HDs are repurposed into public function clusters, including museums, exhibition halls, and art spaces. However, without careful consideration of financial sustainability, these efforts may undermine the long-term viability of the adaptive reuse projects, particularly when public functions are prioritized at the expense of economic feasibility.

While adaptive reuse focuses on repurposing heritage buildings, public space renewal enhances accessibility, functionality, and cultural engagement, ensuring the district remains an active urban hub. The renewal of public spaces is also an essential aspect of heritage district revitalization. Beyond the buildings themselves, these

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spaces—such as streets, squares, and parks—serve as social and cultural hubs, influencing the overall success of the district. The renewal of public spaces ensures that HDs are not only functional but also vibrant, accessible, and integrated into the broader urban fabric. This dual focus on both building reuse and public space renewal is critical for achieving a comprehensive, sustainable approach to heritage district revitalization.

Despite the advances made in heritage district adaptive reuse, significant challenges remain. One of the primary challenges for investors is identifying profitable functions for both heritage buildings and public spaces. Uncertainty regarding demand and financial returns can often lead to unsustainable revitalization efforts, resulting in vacancies or underutilization of both buildings and public spaces. To address these challenges, advanced tools such as GA-BP machine learning models have emerged as frameworks for evaluating and predicting adaptive reuse outcomes. These models provide objective metrics to support decision-making, helping to maximize financial returns while preserving cultural heritage[9–16].

The governance of HD revitalization requires the coordination of multiple stakeholders, including government authorities, enterprises, and local communities. In many cases, government-led and community-led approaches have been used, though these often impose significant financial burdens on the state[17]. As a result, enterprises are becoming increasingly central to the governance of HDs, using market-driven strategies and diversifying funding sources for preservation. This shift necessitates further research into the role of enterprises in heritage district governance and how to balance economic demands with cultural preservation[18].

The Enning Road HD in Guangzhou exemplifies a government-led, enterprise-sponsored approach to heritage district adaptive reuse. The project has faced challenges such as fragmented urban structures, deteriorating housing conditions, unresolved land disputes, and stringent cultural preservation requirements. Despite these challenges, the initiative has achieved notable success in both spatial and economic adaptive reuse. However, it has also been criticized for inadequate stakeholder engagement and the risk of cultural homogenization, issues that are also observed in similar international cases such as the revitalization of Dashilar in Beijing, Tianzifang in Shanghai, and Singapore's Chinatown[19–21].

This study addresses these gaps by examining the case study of the Enning Road HD. Key questions arise: How can quantitative models, such as the GA-BP neural network, be enhanced to incorporate socio-cultural and qualitative factors for more comprehensive predictions and evaluations in HD adaptive reuse? What governance frameworks are most effective in balancing economic, cultural, and social priorities in the adaptive reuse of HDs, particularly under enterprise-led operations? How can stakeholder engagement strategies be optimized to foster inclusive, community-driven heritage district renewal? The research will also explore governance frameworks that balance economic, cultural, and social priorities in adaptive reuse projects, particularly in enterprise-led operations. Through this case study, the paper aims to contribute to broader discussions on sustainable urban development and the challenges of balancing heritage conservation with economic revitalization[22,23].

The paper explores the integration of HD adaptive reuse with multi-stakeholder negotiation mechanisms. First, the theoretical framework is presented, followed by a detailed examination of the adaptive reuse decision-making process. The methodology section outlines the approach used in the study, followed by a discussion of findings and implications for heritage conservation practices.

Literature review and theoretical framework

Research on urban renewal in China has evolved to emphasize various focal areas, as discussed by Zhang and Li[24]. Urban renewal is closely linked to sustainable urban development, encompassing social, economic, and environmental dimensions within a highly intricate framework. Its primary goal is to enhance the physical, socio-economic, and ecological aspects of urban areas through diverse strategies such as redevelopment, rehabilitation, and the preservation of heritage assets.

Mayer, et al[25]. identified two fundamental complexities in urban renewal: system complexity, which refers to the interdependence of the physical and social aspects of cities, and political complexity, which arises from the competing interests of various stakeholders. These complexities create significant challenges in achieving a balance between economic, environmental, and social goals, a difficulty underscored by Couch and Dennemann[26]. As urban renewal efforts aim to improve city landscapes, the challenge remains to balance the often-conflicting objectives of different actors, particularly when considering the implications for sustainability and inclusivity in the process.

Theoretical foundations and key developments in adaptive reuse

Adaptive reuse, as a critical mechanism in urban renewal, has gained significant attention over recent decades. Initially emerging in response to the need for sustainable urban development and the preservation of cultural heritage, adaptive reuse is grounded in sustainability-driven transformations, economic feasibility studies, and policy frameworks that advocate for the repurposing of historic buildings for modern uses[27,28]. However, while these foundational studies have contributed significantly to the field, a closer examination reveals several theoretical and practical limitations that must be addressed.

On one hand, sustainability-driven strategies have been widely celebrated for their environmental benefits. Early works by Bullen and Love ([29]) underscore the potential of adaptive reuse in reducing carbon footprints and minimizing construction waste. Nonetheless, critics argue that these studies often present an overly optimistic view of environmental benefits without adequately addressing the challenges of retrofitting older buildings to meet contemporary energy standards. For example, some contend that while adaptive reuse may lower demolition waste, the energy required for renovation and subsequent operational inefficiencies can offset some environmental gains[31,32].

Economic feasibility studies present another pillar of adaptive reuse literature. Research has demonstrated that adaptive reuse can offer cost-effective alternatives to new construction, particularly in HDs where the intrinsic cultural value of buildings may enhance their economic potential. Yet, this perspective is not without

its detractors. Economic analyses frequently fail to account for hidden costs such as regulatory compliance, the complexity of integrating modern technologies into older structures, and the potential for financial overruns due to unforeseen structural issues. These critiques point to a need for more nuanced economic models that reflect the full spectrum of costs and benefits associated with adaptive reuse.

Policy frameworks also play a critical role in promoting adaptive reuse. In Europe, adaptive reuse has been effectively integrated into urban planning policies, focusing on preserving architectural heritage while addressing modern urban needs[33]. However, scholar argues that such policy frameworks are often too generic, lacking the flexibility required to address the diverse socio-economic and cultural landscapes found within and between cities[34]. Moreover, Smith and Williams[35] emphasize the tension between rigid preservation guidelines and the dynamic nature of urban development. They suggest that while policy initiatives aim to safeguard heritage, they can inadvertently stifle innovation in design and limit adaptive reuse projects' responsiveness to contemporary urban challenges.

Further complicating the discourse, the integration of stakeholder perspectives into adaptive reuse research reveals a critical gap. Although the literature has increasingly acknowledged the importance of community engagement, there remains a disconnect between theoretical models and the realities of multi-stakeholder negotiations. Many studies focus on quantitative outcomes or theoretical constructs without fully addressing how diverse stakeholder interests and power dynamics impact project implementation. This gap calls for more interdisciplinary approaches that merge quantitative analyses with qualitative insights, ensuring that the socio-cultural dimensions of adaptive reuse are adequately considered.

In summary, while the literature provides a robust framework for understanding adaptive reuse—emphasizing environmental, economic, and policy-driven benefits—a critical review exposes significant challenges. These include the underestimation of renovation complexities, hidden economic costs, inflexible policy frameworks, and insufficient integration of stakeholder dynamics. Addressing these critiques is essential for advancing adaptive reuse as a viable strategy for sustainable urban development in the face of evolving urban and environmental challenges.

Multi-Stakeholder dynamics in adaptive reuse

At its core, adaptive reuse seeks to balance heritage conservation with contemporary functionality, advocating for 'conservation through transformation'. This approach recognizes that heritage sites must evolve to remain relevant and viable within modern urban contexts. It also highlights the importance of managing change at an urban scale, necessitating the engagement of local communities and multiple stakeholders to ensure successful integration into the urban fabric.

While many scholars analyze adaptive reuse within the disciplinary boundaries of architecture and heritage conservation, Lanz and Pendlebury[20,22,38] argue that a comprehensive understanding of adaptive reuse must extend beyond architectural concerns to include the economic, social, and operational dimensions of reuse projects. This perspective considers the entire lifecycle of adaptive reuse, including pre-intervention decision-making and post-intervention operational challenges.

However, prevailing definitions often overlook the perspective of tenants and business operators who directly influence the economic sustainability of adaptive reuse projects. If a repurposed building's function does not align with market demand, the project risks financial failure, rendering the reuse effort ineffective. Therefore, adaptive reuse should not only be understood as a physical transformation but also as a strategic mechanism involving economic feasibility, market al.ignment, and stakeholder engagement. In this sense, adaptive reuse can be redefined as 'the process of converting a building to a function significantly different from its original use, with a critical emphasis on economic viability, community engagement, and long-term operational sustainability'. This expanded definition acknowledges that adaptive reuse is not merely about preserving historical structures but also about ensuring their continued relevance and financial viability within a contemporary urban landscape. Adaptive reuse is the process of repurposing historic spaces for new functions while preserving their cultural and architectural significance. Adaptive reuse also plays a key role in urban regeneration, enhancing livability and stakeholder engagement, while mitigating the risk of abandonment due to decay or socio-economic changes. It helps preserve the intrinsic values of heritage in HDs contributing to sustainable urban development[39].

HD adaptive reuse, a specific form of urban renewal, has historically been shaped by a combination of economic forces and top-down government policies. Adaptive reuse in HDs has historically been driven by economic pressures, such as declining property values or industrial disinvestment, pushing for the repurposing of old buildings (OBs) to meet market demands for commercial or residential space[40]. While this can boost property values, it often conflicts with the need to preserve cultural and architectural integrity. Simultaneously, top-down government policies have shaped adaptive reuse by providing regulatory frameworks, such as zoning and preservation guidelines, to balance economic development with heritage conservation. However, the impact of these policies can vary depending on local contexts, especially in rapidly urbanizing cities. Adaptive reuse refers to repurposing OBs for new functions while preserving their cultural significance, whereas urban renewal encompasses broader revitalization efforts, with HD adaptive reuse focusing specifically on HDs. The collaboration between the government, enterprises, and investors in HD adaptive reuse projects has often been marked by minimal community participation, emphasizing capital accumulation and the rapid growth of the real estate market. This top-down approach has resulted in significant tensions, particularly regarding unfair compensation and displacement of residents, as pointed out by Verdini[41]. These conflicts are symptomatic of broader institutional barriers to genuine public involvement, with urban renewal processes frequently favoring economic outcomes over social equity. As a result, residents' voices have often been sidelined, raising concerns about the adequacy of participatory governance in urban renewal initiatives[42,43].

The outcomes of HD adaptive reuse hinge on the coordination and interaction between multiple stakeholders, including the state, private enterprises, and residents. Power imbalances between these groups have led to

marginalized communities, fostering tensions over issues such as compensation and the extent of involvement in decision-making processes. The skewed distribution of power highlights the need for a shift toward more collaborative approaches in urban renewal projects, with a focus on innovation in governance structures. This shift is essential for achieving a more inclusive, transparent, and equitable urban renewal process, one that recognizes the complex dynamics between economic development and social justice.

In parallel with stakeholder-centered strategies, digital technologies and computational models are increasingly leveraged to support heritage management and adaptive reuse decision-making. Tools such as Building Information Modelling (BIM), Geographic Information Systems (GIS), and AI-driven simulations enable more precise assessments of building conditions, predictive maintenance, and scenario testing for redevelopment outcomes[44–46]. These tools not only enhance efficiency but also improve transparency and stakeholder communication by visualizing trade-offs and facilitating evidence-based planning. International case studies further demonstrate how innovative governance and modelling practices contribute to successful adaptive reuse. For example, the Hafencity project in Hamburg integrated public-private partnerships with participatory planning tools to transform a historic port area into a sustainable urban district[47]. Similarly, the Barangaroo redevelopment in Sydney adopted a multi-tiered stakeholder governance model and digital master planning tools to ensure transparency, cultural sensitivity, and ecological integrity[48]. These examples illustrate the global relevance of aligning stakeholder collaboration with digital support systems in the adaptive reuse of heritage districts.

AI intervention in heritage revitalization

To further explore the integration of artificial intelligence in heritage revitalization, recent studies have demonstrated its significant role in optimizing the adaptive reuse of historical blocks. AI's ability to process complex data and generate predictive models has been applied in various aspects of urban renewal, from architectural preservation to urban planning and stakeholder engagement. For example, Foroughi, et al.[49] emphasize AI's role in participatory heritage planning, especially in diverse contexts such as the Windcatchers in Yazd, Iran. Similarly, Abuarkub, et al.[50] investigate adaptive architectural conservation strategies for courtyard houses in Palestine, highlighting AI's capacity to balance heritage conservation with contemporary requirements. The use of Generative Adversarial Networks (GANs) has also gained traction in renovation projects, such as the case study by Zhang, et al.[24], which applied the conditional generative adversarial network model for street facade renovations in Fujian, China, merging historical and modern architectural styles. Studies by Zhang, et al.[24]. These advancements demonstrate the potential of AI to bridge the gap between heritage preservation and modern urban needs, providing crucial insights for sustainable and adaptive reuse strategies.

Research gaps and contributions

While significant progress has been made in understanding the economic and environmental benefits of adaptive reuse, there remains a critical gap in integrating quantitative predictive models with qualitative stakeholder perspectives. Previous studies have predominantly focused on either quantitative evaluation of adaptive reuse outcomes or qualitative analyses of stakeholder dynamics, often neglecting the interplay between these two dimensions. This study addresses this gap by employing a GA-BP neural network model to predict adaptive reuse outcomes while complementing the quantitative analysis with qualitative insights from stakeholder interviews.

Our primary contribution lies in utilizing AI-driven predictive modeling as a tool to assess and optimize the success of revitalization efforts in HDs. This approach is complemented by integrating the perspectives of multiple stakeholders, providing a more comprehensive view of the challenges and opportunities involved in adaptive reuse. The combination of AI modeling and stakeholder input allows for more effective decision-making and resource allocation in heritage conservation projects. This dual approach allows for a more comprehensive evaluation of adaptive reuse strategies, particularly in balancing cultural heritage conservation with economic development. By combining advanced machine learning techniques with qualitative stakeholder analysis, this study offers a data-supported framework that can assist decision-makers in navigating the complexities of historic district regeneration.

Theoretical framework

As discussed in the theoretical background, the stakeholder theory extends beyond the identification of stakeholders to encompass value creation. In urban contexts, value creation is a key concern in sustainable urban strategies, network governance, and urban marketing, as it fosters better urban governance, promotes the recognition of the common good, and facilitates the democratization of urban management. Further studies could explore the specific mechanisms of value creation in HD redevelopment, particularly in the context of different urban environments.

In this study, the stakeholder theory provides a humanist approach to HD revitalization by emphasizing the importance of stakeholder recognition and participation in the negotiation process. A stakeholder negotiation mechanism is established among three key actors: the government, enterprises, and residents. Enterprises invest in the heritage district by acquiring or leasing residential properties from residents through negotiated compensation agreements. This process ensures that property transactions are conducted fairly and transparently, aligning economic incentives with heritage conservation goals.

Following the negotiation phase, enterprises engage in adaptive reuse strategies to make the heritage district more suitable for market demands. This includes public space enhancements to improve accessibility and aesthetic appeal, as well as interior refurbishments to transform former residential buildings into commercially viable spaces, such as restaurants, retail shops, and cultural venues. Once the redevelopment process is completed,

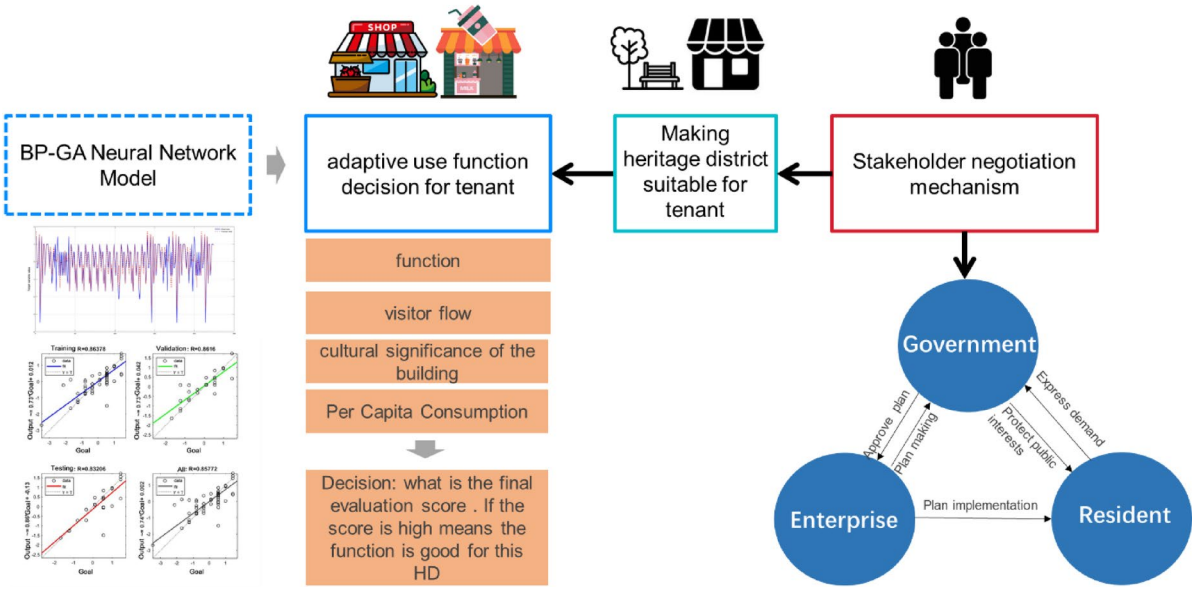

Fig. 1. Theoretical Framework.

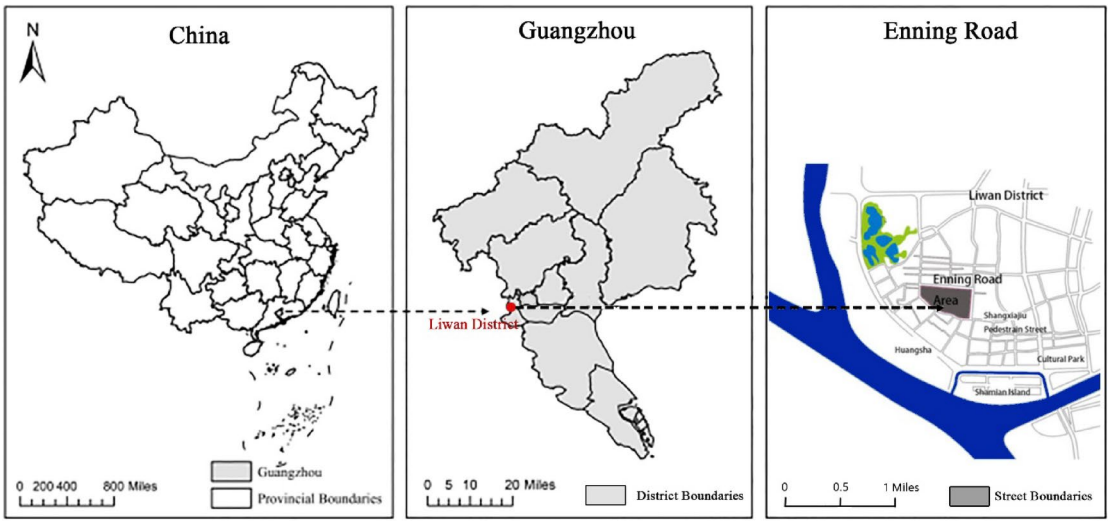

Fig. 2. The location of Enning Road historic district.

enterprises lease the renovated properties to tenants, who then determine their specific business operations within the district.

To support optimal decision-making, this study incorporates the GA-BP neural network model. The GA (Genetic Algorithm) component optimizes redevelopment strategies by selecting the most effective renovation and leasing approaches, while the BP (Backpropagation) neural network component learns from historical adaptive reuse projects to assess market feasibility. This AI-driven decision-support mechanism helps enterprises and stakeholders align adaptive reuse efforts with market demands, ensuring both economic and cultural sustainability.

By integrating stakeholder negotiations, adaptive reuse principles, and AI-driven decision-making, this framework provides a comprehensive model for HD revitalization. It promotes collaborative decision-making, sustainable development, and long-term viability, ensuring that heritage districts are not only preserved but also successfully integrated into contemporary urban economies. (See Fig. 1).

Methodology

Study context

Enning Road HD, located in Liwan District, Guangzhou, is a block with strong local characteristics. The Enning Road HD locates west of Shangxiajiu Pedestrian Street (See Fig. 2). Built in 1931 and located 8 km from the city

center, Enning Road exemplifies the shift from demolition to preservation in urban regeneration. The renewal process of Enning Road, starting in 2007, involved key milestones: designation as a HD in 2014, Enning Road's Phase I micro-renovation in 2016, and pilot protection plans by 2019.

Enning Road reflects conflicts between rapid urban changes and existing planning systems, serving as a platform for multi-stakeholder negotiations and balancing diverse interests, making it a landmark case in China's urban renewal efforts.

Stakeholder mapping methodology

To systematically analyze the diverse interests and influence of stakeholders involved in the adaptive reuse of Enning Road, a structured stakeholder mapping approach was employed, categorizing stakeholders based on their level of influence and interest to ensure a comprehensive understanding of their roles in decision-making processes. Stakeholders were classified into four primary groups: government authorities, including municipal planning departments and heritage conservation offices responsible for policy-setting and project approval; private investors and developers, encompassing real estate developers, business owners, and financial institutions involved in funding redevelopment projects; local residents and community organizations, including displaced and remaining residents, cultural groups, and advocacy organizations directly impacted by redevelopment decisions; and academia and experts, consisting of heritage scholars, urban planners, and architectural conservation specialists contributing insights on sustainable revitalization strategies. A stakeholder matrix framework was used to evaluate each group based on two dimensions—Influence, the extent to which a stakeholder can shape policies or public opinion, and Interest, the degree of direct impact a stakeholder experiences from the redevelopment process. This framework categorized stakeholders into four groups: key decision-makers (high influence, high interest), such as government agencies and major developers; consulted stakeholders (high influence, low interest), including academics and external investors; affected groups (low influence, high interest), such as local residents and small business owners; and peripheral stakeholders (low influence, low interest), including external heritage enthusiasts and the general public. To ensure a balanced representation of viewpoints, semi-structured interviews were conducted with representatives from each stakeholder category, focusing on conservation priorities, economic feasibility, and governance challenges. Additionally, content analysis of policy documents, media reports, and public consultation records was undertaken to triangulate stakeholder positions. This stakeholder mapping approach provided critical insights into the power dynamics and conflicting interests within the adaptive reuse process, helping to contextualize the challenges faced in the adaptive use of Enning Road.

Focus group interview method

To explore the experiences associated with the renewal projects of HDs, this study employed focus group interviews as the primary data collection method. This approach was selected due to its ability to facilitate dynamic group discussions, providing richer insights into stakeholders' perspectives compared to individual interviews. According to Peters and Schnitzer[47], focus groups are particularly effective in exploring reactions to new strategies and initiatives, making them ideal for assessing stakeholders' views on HD regeneration. The group size was between 6 and 9 participants per session, which is the recommended range for generating productive discussions[53].

Participant selection

Participants were selected using purposeful sampling, ensuring that individuals with direct experience and involvement in HD renewal were included. The selection process focused on individuals with expertise in heritage preservation, urban development, and community engagement. Specifically, participants included investors, local authorities, and community representatives, all of whom played a role in the regeneration of the HDs in question. The recruitment of participants was facilitated through the network of the enterprise responsible for hosting the HD renewal project, with outreach methods such as mailings and newsletters.

A total of 20 participants were recruited, consisting of 11 men and 9 women aged between 25 and 60 years, based in China. Three separate focus groups were formed, with each group reflecting a balance of perspectives from the selected stakeholder categories(See Table 1). Informed consent was obtained from all participants, and the research was carried out following ethical guidelines approved by the academic board of Guangzhou Urban Planning and Design Co., Ltd.

Data collection

The focus group interviews were conducted between May and July 2023 and lasted an average of one hour and 29 minutes. The interviews were structured around three key themes: stakeholder demands, under renewal, and post-renewal phase, which were derived from renewal theory. The structured guidelines ensured consistency across interviews while allowing for flexibility in responses. The focus groups were conducted in a collaborative environment, allowing participants to interact and provide diverse perspectives on HD regeneration. This method helped achieve data saturation, ensuring that key themes and challenges were thoroughly explored.

Data analysis

To ensure the reliability and validity of the findings, a multi-step analysis process was followed. The initial stage involved reading through the transcripts to gain an overview of the data. Next, MAXQDA software was used to assist in the coding process, organizing the data into manageable themes. Throughout this process, the research team regularly reflected on the data, aligning and refining the coding structure to ensure consistency. This iterative approach helped produce a coherent set of predefined themes, which were used to analyze the focus group discussions in detail.

Number	Code	groups	Stakeholders	Gender
1	G1#1G	G1	government	Female
2	G1#2D	G1	enterprise	Male
3	G1#3G	G1	urban planner	Male
4	G1#4 M	G1	media	Male
5	G1#5 N	G1	NGO	Female
6	G1#6D	G1	enterprise	Male
7	G1#7D	G1	enterprise	Male
8	G1#8S	G1	specialist	Male
9	G1#9R	G1	resident	Female
10	G1#10S	G1	Shop keeper	Male
11	G1#11S	G1	Shop keeper	Male
12	G2#12G	G2	government	Female
13	G2#13 M	G2	media	Female
14	G2#14D	G2	enterprise	Female
15	G2#15D	G2	enterprise	Male
16	G2#16U	G2	urban planner	Female
17	G2#17U	G2	urban planner	Female
18	G2#18S	G2	specialist	Male
19	G2#19R	G2	resident	Male
20	G2#19 N	G2	NGO	Female

Table 1. Basic information of interviewees.

Dimension hierarchy	Index	Calculate method
People amount	Visitor flow	Dazhong Dianping has the capability to crawl data
historical feature	The culture level of the building	If the building is a National Cultural Heritage site, the score is 7; for a provincial site, it is 6; a city-level site scores 5; a district-level site scores 4; a historic building ID scores 3; a regular old building scores 2; and a new building scores 1.
Adaptive use	Per capita consumption	Dazhong Dianping has the capability to crawl data
	Functional type	Dazhong Dianping has the capability to crawl data

Table 2. Independent variables.

Limitations and ethical considerations

This study was approved by the Institutional Review Board of Guangzhou Urban Planning and Design Co. Ltd. All participants provided informed consent before participating in the interviews. To ensure confidentiality, personal identifiers were removed, and anonymized data was used for analysis. Participation was voluntary, and interviewees had the right to withdraw at any stage without consequences. One limitation of this study is its reliance on self-reported data, which may introduce response bias. Additionally, while ethical guidelines were followed, potential biases in stakeholder perspectives could have influenced the findings. Future studies should consider broader participant representation and the triangulation of data sources to enhance validity.

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Adaptive use index system and the data sources

We defined the adaptive use system as encompassing three core elements: the adaptive reuse of the building, the daily visitor count, and the cultural background and value of the building. Independent variables for evaluating adaptive reuse in OBs within HDs were identified as follows (see Table 2): visitor flow, cultural significance of the building, per capita consumption, and functional type. These variables serve as key indicators to assess the success of adaptive use efforts.

The data for these variables were sourced from Dazhong Dianping, a popular application used to locate local restaurants, hotels, and shops, which provides geolocation and descriptive details about businesses within the HD. To gather the necessary data, we implemented a web-crawling process to extract information on all shops operating within the HD. This dataset was then integrated into a GA-BP neural network model for analysis.

The dependent variable in our study is the evaluation score, which measures public satisfaction with the adaptive reuse of the buildings. This score serves as a benchmark to determine whether the adaptive use efforts align with visitors' expectations and preferences. By correlating the independent variables with the evaluation scores, the study aims to provide a robust framework for understanding the factors that contribute to the successful adaptive reuse of OBs.

GA-BP neural network model

This research uses a GA-BP neural network model to predict some important factors of HD adaptive use, which is a multi-layer feed-forward neural network trained according to the error back propagation algorithm after optimizing weights and thresholds by a genetic algorithm, and the initial weights and thresholds of BP neural network are optimized by a genetic algorithm to reduce the model error and improve the accuracy of prediction[54]. The flow is shown in Fig. 3. The experimental protocol was approved by the academic board of Guangzhou Urban Planning and Design Co., Ltd.

BP neural network

A BP neural network is a multi-layer feedforward neural network characterized by the forward propagation of data and the backward propagation of error signals. It consists of three key components in its structure: the input layer, the hidden layer, and the output layer. Consequently, the network can be constructed based on these defining features and its topology[55,56].

Let the number of nodes in the input layer, hidden layer, and output layer be denoted as,, and, respectively. The weight from the input layer to the hidden layer is ω, the weight from the hidden layer to the output layer is ω. The bias terms for the hidden and output layers are represented as,. The learning rate is, and the excitation function (EF) is given by g(x), where is the input value. The EF can be calculated using the following formula[57]:

$$g(x) = \frac{1}{1+e^{-x}} \tag{1}$$

The hidden layer output can be calculated using the following formula:

$$H_j = g(\sum {}^{n}_{t=1}\omega_{ij}x_t + a_j) \tag{2}$$

The output layer output can be calculated using the following formula:

$$Q_k = \sum {}^{l}_{f=1} H_j \omega_{jk} + b_k \tag{3}$$

The equation of Error analysis is shown as Formula:

$$Y_k - O_k - e_k \tag{4}$$

The update of weights can be calculated using the following formula:

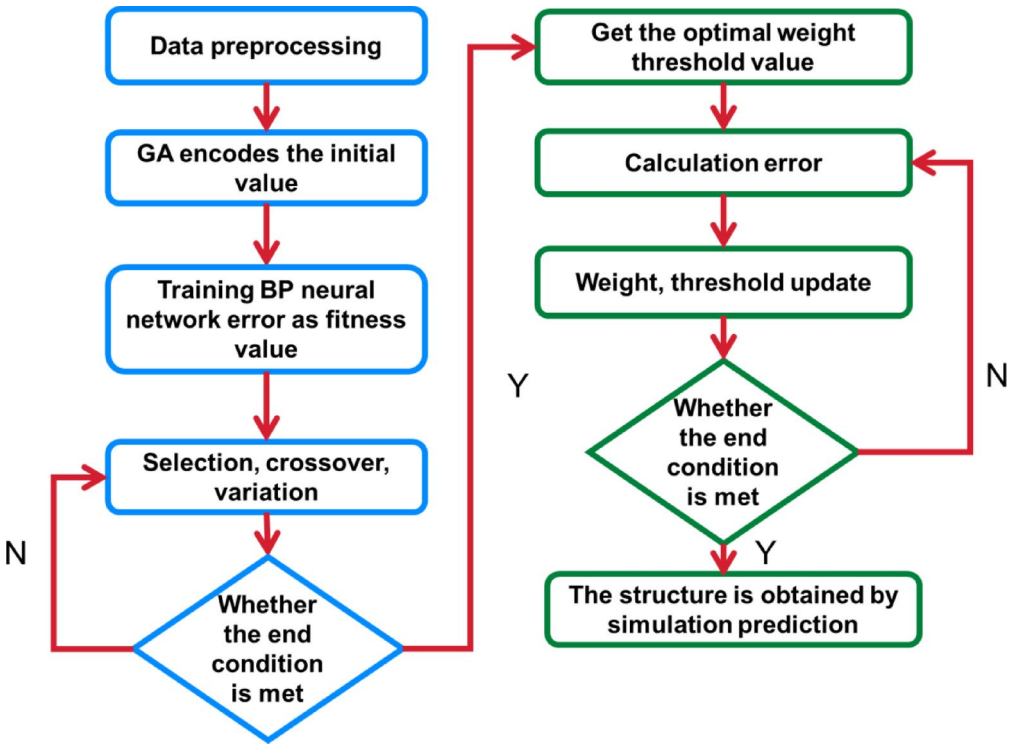

Fig. 3. GA-BP neural network algorithm flow.

$$\begin{cases} \omega_{ft} = \omega_{ft} + \eta H_f(1 - H_j)x_i \sum_{k=1}^{m} \omega_{jk} e_k \\ \omega_{fk} = \omega_{fk} + \eta H_j e_k \end{cases} \tag{5}$$

The update of offset can be calculated using the following formula:

$$\begin{cases} a_f + \eta H_f (1 - H_j) x_i \sum_{k=1}^{m} \omega_{jk} e_k \\ b_k = \omega_{fk} + \eta e_k \end{cases} \tag{6}$$

Genetic algorithm to optimize BP neural network

The GA is an optimization method inspired by the principles of natural selection and genetic mechanisms. It emulates the biological evolution process by performing operations such as replication, crossover, and mutation to generate problem solutions. Solutions with lower fitness function values are gradually discarded, while those with higher fitness function values are retained and amplified. Over N generations, the algorithm evolves toward producing high-fitness individuals, representing the optimal solutions to the target function.

On the other hand, BP neural networks exhibit strong local search capabilities but are prone to getting trapped in local minima. By contrast, GA is characterized by adaptability, global optimization potential, and implicit parallelism. Combining GA with BP neural networks leverages the strengths of both approaches, enabling automatic optimization and enhancing learning efficiency. The detailed optimization process is illustrated in Fig. 3. In this study, a GA was employed to optimize the BP neural network, enhancing its predictive accuracy in determining the most suitable adaptive reuse types for HDs. The GA effectively refines the initial weights and biases of the BP network, mitigating issues such as local minima and slow convergence. By integrating GA into the BP framework, the model achieves higher accuracy and stability, which is crucial for addressing the complex and context-specific nature of historic district revitalization. This approach is particularly well-suited for the Enning Road project, as it enables a more precise evaluation of reuse strategies by considering multiple influencing factors, such as historical value, stakeholder preferences, and economic feasibility. Consequently, the GA-BP model provides a data-driven decision support tool that can guide sustainable and culturally sensitive redevelopment efforts.

Applicability and limitations of the GA-BP neural network model

The GA-BP neural network model has been widely employed in predictive analytics and decision support systems, particularly in HD adaptive reuse. By integrating multiple variables such as visitor flow, cultural significance, per capita consumption, and functional type, the model aims to evaluate and predict adaptive use success. While this approach provides an empirical foundation for decision-making, its applicability and limitations must be critically assessed.

The model proves highly valuable in objectively evaluating adaptive use outcomes, offering a data-driven basis for assessing different adaptive reuse strategies. By incorporating both economic and cultural factors, it goes beyond conventional financial feasibility assessments, ensuring that heritage conservation remains a priority. Additionally, its ability to simulate multiple scenarios enhances stakeholder decision-making, supporting urban planners, policymakers, and investors in identifying optimal interventions while mitigating conflicts. Its scalability further strengthens its relevance, allowing it to be adapted for various HDs beyond Enning Road.

However, despite its advantages, the GA-BP model has inherent limitations. Its predictive accuracy heavily depends on data quality and availability. Without comprehensive datasets on visitor behavior, economic performance, or cultural significance, the model's reliability diminishes. Furthermore, it fails to capture qualitative factors such as community sentiment, governance structures, and policy changes, which are crucial in determining the success of adaptive reuse projects. The complexity of HDs, shaped by unique regulatory frameworks and market dynamics, also presents challenges in generalizing the model's application across diverse urban contexts.

In conclusion, while the GA-BP neural network model offers a promising approach for evaluating adaptive reuse in HDs by combining economic, cultural, and functional parameters into a predictive framework, its effectiveness is contingent on data quality, contextual adaptability, and the inclusion of socio-political and environmental considerations. Moreover, data analysis alone is insufficient; negotiation processes and implementation strategies must also be carefully considered. A comprehensive understanding of these aspects should be obtained through interviews with key stakeholders. Addressing these limitations through enhanced qualitative integration and sustainability-focused refinements will ensure the model's robustness and broader applicability in urban heritage management.

Results

GA-BP model validation and prediction of HD adaptive use

The training results obtained from the GA-BP neural network, as illustrated in Fig. 4, reveal regression coefficients of 0.86378, 0.8616, and 0.83206 for the training group, verification group, and test group, respectively, with an overall regression coefficient of 0.85772[58,59]. While these values suggest a strong correlation between the simulated and measured results, the variability across groups indicates potential areas for further optimization of the model's parameters (See Fig. 5).

Critically, the model's high accuracy in predicting outcomes for old building adaptive use underscores its potential as a decision-making tool. However, the reliance on a limited set of input variables—average expenditure per person in shops, foot traffic, and cultural value—may not fully capture the multifaceted dynamics influencing satisfaction with HD regeneration projects. While these factors are significant, the

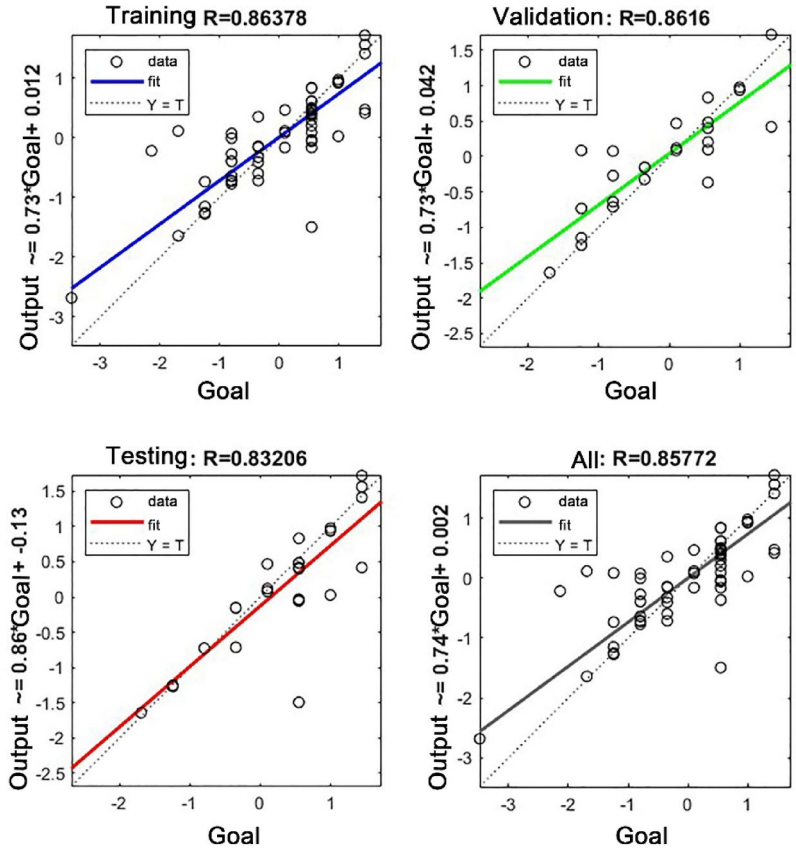

Fig. 4. Neural network training results.

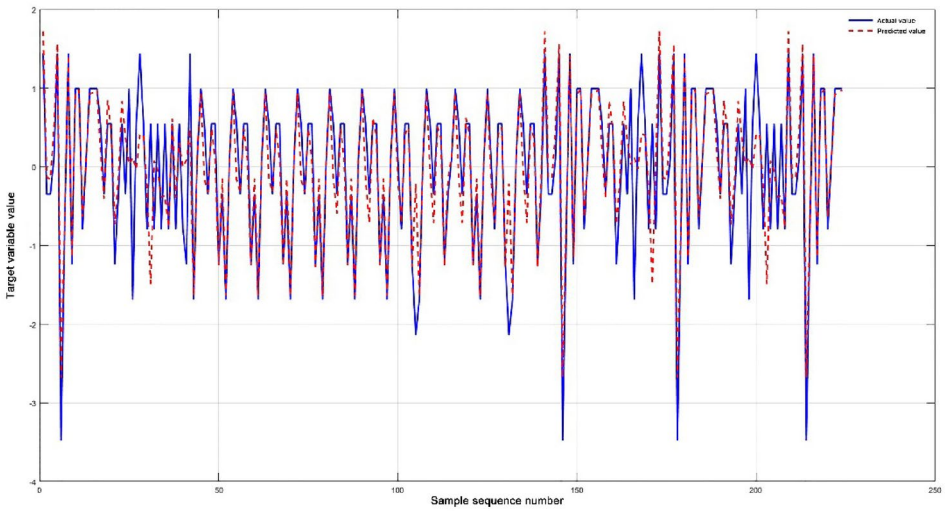

Fig. 5. Predicted and actual values on the training set.

exclusion of variables such as community engagement, historical authenticity, or environmental impact could limit the model's comprehensiveness and practical utility in diverse contexts.

Moreover, the results highlight the importance of integrating quantitative measures with qualitative assessments to better address the complex socio-cultural and economic dimensions of HD adaptive use. As it stands, the model provides a promising yet incomplete framework for evaluating project success. Future iterations should explore incorporating additional variables and refining the model to enhance its predictive robustness and adaptability across different scenarios.

Multi-stakeholder negotiations process

The indicators of social sustainability from the perspective of deterministic stakeholder demands, Government empowerment and transfer profits to enterprise, resident demand can be explained with the model presented in Fig. 6. At this stage, which is referred to as "selective coding" in qualitative research, basic categories and subcategories can be presented holistically.

Deterministic stakeholder demands analysis

Enning Road was in the legal protection area of historical and cultural district from 2014, so it needed to be protected under the legal plan which meant it could not be totally demolished. However, as part of the districts have been demolished and broken, government needed to repair the urban fabric, revitalize state-owned buildings, and improve the city negative image. 'Enning Road actually had a strong demand for redevelopment. By responding to the government's bidding documents, we obtains the right to operate the project and played the role of balancing economic interests and public interests' (G1#2D-3). 'The enterprise obtains certain economic benefits by investing in construction in exchange for the subsequent operation income of the project. At the same time, they also need to guarantee public interests such as regional public environment, service facilities and architectural features, and deal with conflicts and conflicts with local residents' (G2#12G −5). 'The core needs of enterprise include the construction quantity to meet the profit demand, the use space to meet the investment operation demand, and the construction plan and period to meet the cost control demand' (G2#15D-9). 'The renovation cost of Enning Road is relatively high in similar micro-renovation projects. On the one hand, the renovation needs to protect the architectural characteristics, but also consider the hardware cost, capital cost, manpower and operating cost. On the other hand, factors such as the location, value of the renovation project and the difficulty of the on-site building renovation will also have a greater impact on the cost'(G1#7D-9).

Therefore, for the 34,000 square meters of public housing buildings handed over by the government, most of them are brick and wood and mixed structures, and the base area is basically less than 100 square meters, which is difficult to meet the future investment and operation needs of enterprises in terms of quality and scale. 'We wanted to rebuild this part of the building to meet the needs of space, construction costs and construction time. As for the 36,000 square meters of buildings that have been rebuilt, we hope to meet the requirements of protection planning and height control and carry out a large design' (G1#6D −20). These core requirements of the enterprises were in conflict with the expectations of stakeholders such as the government, experts, media and social groups for Enning Road HD to extent, and further negotiation is needed. Local residents mainly suffer from the poor living environment and need to obtain relatively ideal benefits through the old city reconstruction. 'I think it is a good thing to renovate those houses that have been neglected and improve the surrounding environment' (G1#9R −20). It can be seen that the three definite stakeholders of government, enterprises and residents form a three-way dialectical relationship of Power Capital Society (See Fig. 6).

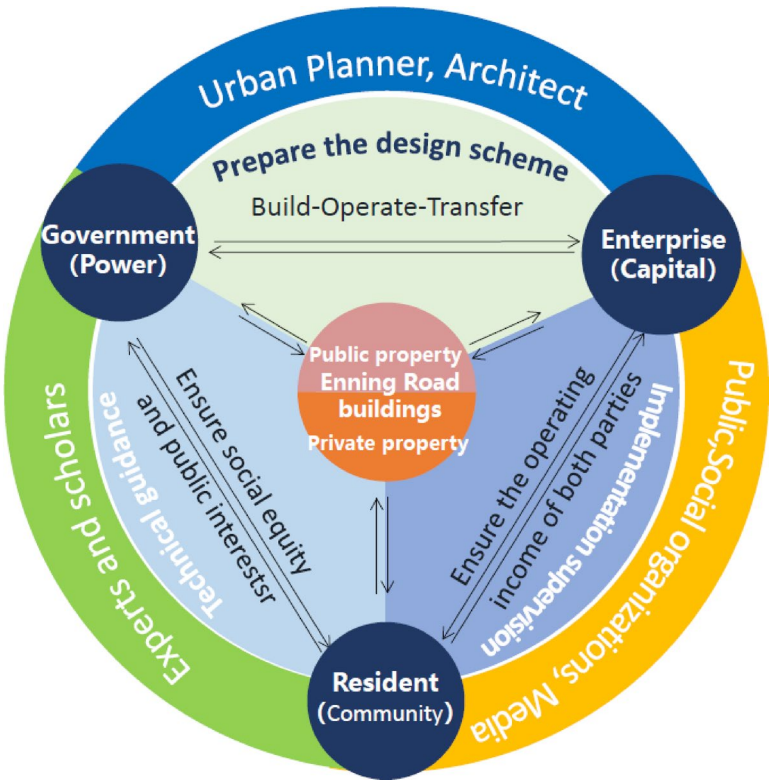

Fig. 6. Enning Road project stakeholder relationship.

Government empowerment and transfer profits to enterprise

'The 2017 plan aimed to balance historical preservation with urban redevelopment. Key measures included defining protection boundaries, height restrictions, and optimizing land use and traffic' (G2#16U −1). However, 'tensions arose between conservation methods and the flexibility needed for development, exacerbated by conflicting stakeholder interests'(G2#15D-2).

'Redevelopment required multi-stakeholder negotiations and a unified blueprint' (G1#3G −4). 'We facilitated a public-private partnership, transferring property usage rights to enterprises while retaining oversight. This model sought to align interests through principles like modernized standards, protection adherence, minimal disruption, and aesthetic coherence t' (G2#12G −9).

Despite structured planning, clashes between government plans and enterprise-driven execution highlighted the need for more flexible, dynamic planning mechanisms. 'Enning Road's case offers a potential model for balancing heritage preservation with urban renewal, warranting further research into its long-term impacts'(G2#19 N-1).

Resident demands and consultation process

The second phase of the Enning Road redevelopment exposed acute tensions among residents, property owners, and enterprises, revealing the complexities of balancing heritage conservation with urban renewal. 'The prolonged expropriation process displaced approximately 280 local families, significantly disrupting their lives and fueling resistance to government actions'(G2#19R-4). 'This resistance was compounded by residents' simultaneous desire for faster environmental transformation, highlighting the inherent contradictions in urban redevelopment initiatives'(G1#5 N-2).

The construction phase further exacerbated these tensions. 'Structural damage to existing buildings, noise pollution, and traffic disruptions negatively impacted the quality of life for remaining residents, creating friction between them and the enterprises'(G2#13 M-1). 'Marginalized groups, such as the elderly and low-income families, faced heightened challenges due to their limited organizational capacity and often relied on media channels to amplify their concerns. This reliance on external advocacy underscored the absence of effective mechanisms for these groups to directly engage in decision-making processes'(G2#19R-2).

In response to mounting social tensions, a co-creation committee was established, aiming to facilitate direct communication between stakeholders and mitigate conflicts. Comprising 25 members, including 12 resident representatives, the committee sought to balance diverse interests. While it provided a platform for residents to voice their concerns and contributed to smoother communication during renovation activities, its practical effectiveness was limited. Key stakeholders, including government authorities and enterprises, displayed inconsistent engagement, and the committee struggled to mediate deeply entrenched conflicts.

The challenges faced by the co-creation committee underscored critical weaknesses in participatory governance mechanisms. The inability to reconcile conflicting interests through formal meetings revealed structural barriers to effective collaboration. For instance, divergent priorities between enterprises focused on economic outcomes and residents advocating for social equity created persistent deadlocks. These challenges were further illustrated by the committee's difficulty in addressing the specific needs of vulnerable groups, who remained marginalized throughout the redevelopment process.

The Enning Road redevelopment serves as a critical case study in navigating the tensions between development goals and social equity in heritage conservation. The project's evolution into a high-profile social event, coupled with the establishment of the co-creation committee, reflects a growing demand for inclusive and participatory approaches to urban planning. However, the limited success of the committee highlights the need for more robust governance structures capable of addressing the complexities of stakeholder dynamics. These include enhanced participatory governance, namely, establishing mechanisms that ensure consistent and meaningful engagement of all stakeholders throughout the project lifecycle; transparency in decision-making, namely, implementing transparent processes for negotiations and project implementation to build trust among stakeholders and minimize conflicts; and empowerment of vulnerable groups, namely, providing targeted support for marginalized populations, such as legal assistance and advocacy training, to amplify their voices in decision-making forums.

Figures 7 and 8 illustrate the stakeholder dynamics and participatory challenges encountered during the project, highlighting critical areas for improvement in future initiatives. These include fostering collaboration between stakeholders, aligning development objectives with social equity considerations, and ensuring that heritage conservation projects do not disproportionately disadvantage vulnerable communities.

Ultimately, the Enning Road redevelopment underscores the importance of adopting a holistic approach to urban planning that balances economic development with social equity and cultural preservation. By addressing these multifaceted challenges, future projects can create more sustainable and inclusive urban environments that reflect the needs and aspirations of all stakeholders.

Discussion

The findings of this study highlight the critical need to integrate both quantitative and qualitative assessments in addressing the multifaceted socio-cultural and economic dimensions of HD adaptive reuse. The use of the GA-BP neural network model provided predictive insights into adaptive reuse outcomes, identifying key factors such as average expenditure, foot traffic, and cultural value as critical in selecting appropriate functions. These findings underscore the necessity of balancing economic viability and cultural preservation in the decision-making process.

Adaptive reuse refers to the process of repurposing existing heritage structures for new functions while maintaining their historical and cultural significance. This approach is integral to HD revitalization as it allows for economic and social benefits while preserving architectural identity. Meanwhile, a sustainable transformation

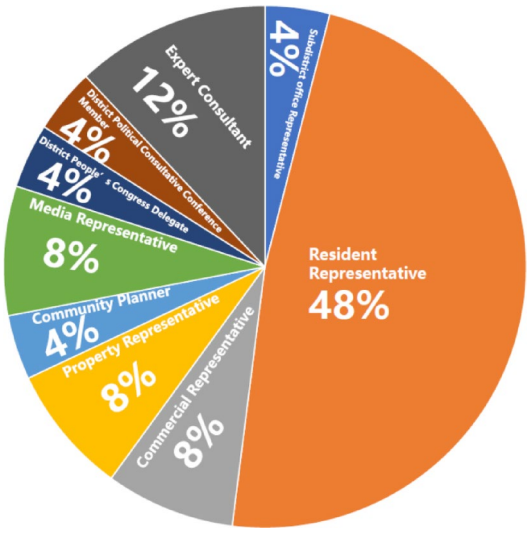

Fig. 7. Enning Road Project co-creation committee composition.

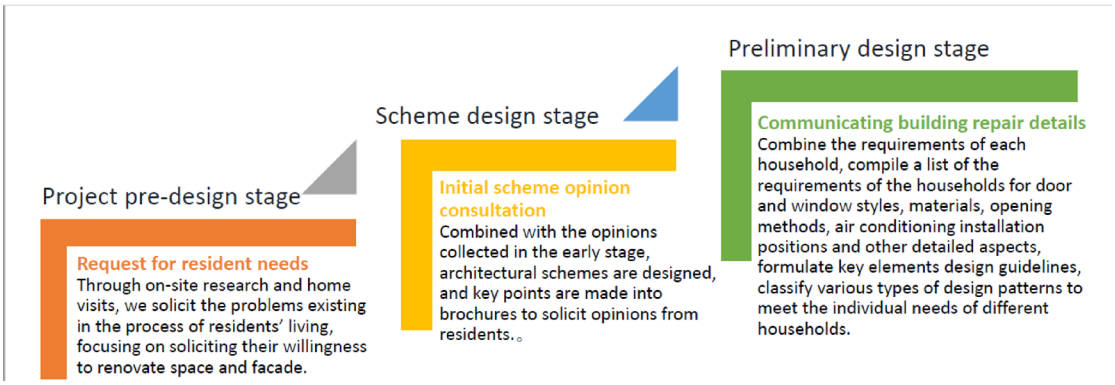

Fig. 8. Enning Road project shophouse entry communication.

mechanism refers to a structured framework that ensures long-term viability through policy support, financial incentives, stakeholder engagement, and urban planning strategies. This mechanism facilitates the reconciliation of conservation objectives with urban development pressures, ensuring that historic districts remain culturally vibrant and economically resilient.

This study contributes to heritage conservation research by integrating the GA-BP neural network with qualitative interview data, providing a data-driven approach to adaptive reuse decision-making. While GA-BP has been widely applied in various predictive modeling tasks, its use in assessing historic block revitalization remains underexplored. By incorporating both physical attributes and stakeholder perspectives, this study enhances the objectivity of reuse potential evaluations and refines investment decision-making. Moreover, the proposed framework is adaptable to other historic districts facing similar challenges of balancing conservation with urban development, making it relevant beyond the local context. Future research could further validate this approach in diverse cultural settings to enhance its applicability on a global scale. By integrating the GA-BP neural network with qualitative interview data, this study presents a data-driven approach to adaptive reuse decision-making. While GA-BP has been widely used in predictive modeling tasks, its application to HD revitalization remains underexplored. By incorporating physical attributes and stakeholder perspectives, this study enhances the objectivity of reuse potential evaluations and refines investment decision-making. Moreover, the proposed framework is scalable and adaptable to other HDs facing similar conservation and redevelopment challenges. Future research could further validate this approach across diverse cultural settings to enhance its global applicability.

An effective adaptive reuse mechanism requires a structured decision-making process that integrates function matching, stakeholder engagement, and public space renewal. In this study, the GA-BP model identified optimal land-use functions based on economic and cultural factors. However, the selection process involved more than just algorithmic predictions—qualitative insights from stakeholder interviews played a crucial role in contextualizing model outcomes. This multi-layered approach ensured that heritage reuse decisions were both data-informed and culturally grounded.

key limitation observed in the case study was the government adoption of the Build-Operate-Transfer (BOT) model. While this approach enhanced market efficiency and resource allocation autonomy, it also created tensions between economic and cultural objectives. The profit-driven nature of the BOT model required external oversight to prevent cultural heritage from being compromised for commercial gains. The co-creation committee, established to integrate public feedback, faced challenges due to the underrepresentation of key stakeholder groups, particularly media and social organizations. This exclusion weakened the effectiveness of participatory governance, highlighting the need for more inclusive decision-making processes.

The renewal of public spaces was a crucial yet underexplored aspect of Enning Road's regeneration. While significant infrastructural improvements were made, the project did not fully preserve the community's cultural identity, which is central to the district's significance. The redesign of public spaces should have focused on social integration by facilitating interactions between long-term residents, tourists, and new businesses through community events and cultural programs. Retaining historical elements, such as traditional signage, street markets, and architectural motifs, would have strengthened authenticity. Additionally, enhancing foot traffic and business activity through strategic public space revitalization would have aligned with global best practices in heritage-led urban regeneration. However, limited interaction between new businesses and original residents created a cultural disconnect, further undermining the potential for an inclusive and community-driven renewal process. Future projects should prioritize community engagement in public space redesign to enhance social cohesion and cultural continuity.

Governance plays a crucial role in ensuring balanced and equitable HD regeneration. In the case of Enning Road, the BOT model placed significant control in the hands of private enterprises, which focused primarily on return on investment. This resulted in conflicts between commercial interests and community needs. A key governance challenge was the limited effectiveness of stakeholder coordination mechanisms. The co-creation committee aimed to bridge the gap between enterprises, government authorities, and the public, but its lack of diverse representation weakened its ability to advocate for resident concerns, such as housing affordability and cultural preservation. Moving forward, alternative governance models, such as public-private partnerships with cultural oversight committees or community land trusts, could help strike a better balance between economic incentives and heritage conservation.

The challenges faced by Enning Road regeneration mirror similar dilemmas observed in other global heritage districts. Beijing Dashilar and Shanghai's Tianzifang have faced gentrification pressures, rising property values, and the displacement of long-term residents. Singapore Chinatown has struggled with government-led heritage preservation efforts that clashed with community concerns over authenticity. Meanwhile, Barcelon El Raval and London Covent Garden successfully implemented adaptive reuse strategies, transforming historic buildings into creative hubs, boutique hotels, and mixed-use spaces that balance economic sustainability with cultural authenticity. Unlike some of these projects, Enning Road approach lacked a clear strategy for fostering interaction between businesses and the local community. To maximize the long-term benefits of adaptive reuse, future regeneration efforts should integrate participatory governance, cultural co-creation, and innovative financial mechanisms to ensure that economic viability does not overshadow cultural heritage preservation.

Despite the governance and cultural challenges, technological innovation presents new opportunities for enhancing adaptive reuse strategies. This study demonstrated how the GA-BP neural network can be leveraged to optimize decision-making. Similar AI-driven models have been applied in European heritage conservation projects, where machine learning supports adaptive reuse potential assessments and resource allocation strategies. By integrating predictive analytics, heritage planners can make more data-driven, strategic decisions that align with both economic and cultural goals. Nonetheless, we recognize that relying solely on Dazhong Dianping may not fully capture the perspectives of residents, as the platform primarily reflects the opinions of visitors rather than long-term inhabitants. Residents may have different concerns, such as housing affordability, infrastructure quality, and community cohesion, which are not typically reflected in tourist reviews. Future research should integrate additional data sources, such as household surveys or interviews with residents, to provide a more comprehensive understanding of user needs in the renovation process. This would ensure a balanced perspective that considers both tourism-driven development and residential well-being.

The regeneration of heritage districts presents both challenges and opportunities that extend beyond the case of Enning Road. A key challenge is balancing heritage conservation with economic viability, particularly in the face of urban development pressures. This study emphasizes that successful adaptive reuse requires a holistic decision-making framework that incorporates quantitative models (GA-BP) and qualitative insights (stakeholder interviews). A strong governance model should prioritize inclusive participation and ensure that commercial interests do not override cultural preservation. Additionally, public space renewal should actively promote social integration and cultural engagement. The use of AI-driven tools can further refine predictive analytics and optimize adaptive reuse strategies. By comparing Enning Road with global heritage regeneration cases, this study highlights the shared challenges of balancing conservation and commercialization while emphasizing the need for context-specific solutions. Future research should further explore how adaptable AI frameworks, like the GA-BP model, can be refined and implemented in diverse urban settings to enhance the sustainability and inclusivity of historic district adaptive reuse.

Conclusion

The selection of functional uses within HDs is a critical determinant of their economic viability. Economic feasibility, which directly impacts the sustainability of adaptive reuse projects, has been consistently identified as a key consideration in the decision-making process for tenants. As adaptive reuse projects often involve significant upfront costs, including renovation and compliance with regulatory standards, ensuring that the new functions align with market demands is essential for securing financial returns. From a tenant perspective, the economic success of a HD revitalization depends not only on preserving its cultural significance but also on

integrating contemporary uses that foster long-term viability and community engagement. By addressing both the financial and cultural dimensions, sustainable adaptive reuse becomes achievable, ultimately contributing to the enduring success of heritage buildings within evolving urban landscapes. Successful adaptive reuse requires a coordinated, multi-stakeholder approach involving consensus-building, negotiation, and strategic partnerships to balance economic, social, and cultural objectives.

This study yields three key findings: (1) Predictors of sustainable adaptive reuse-cultural significance, per capita consumption, and functional type serve as reliable indicators of whether an adaptive reuse function is sustainable for revitalization institutions. (2) Governance and decision-making-enhancing participatory governance and ensuring transparency in decision-making processes are essential for the successful implementation of adaptive reuse projects. (3) Stakeholder dispute resolution-providing targeted support for marginalized populations, along with integrating professional mediators or third-party facilitators, can effectively resolve conflicts and improve project outcomes.

Despite these insights, challenges persist in mobilizing and organizing public participation, which is crucial for fostering long-term stakeholder collaboration. The inherent complexities of HBs necessitate innovative governance frameworks that address their socio-economic and institutional specificities. While enterprise-led mechanisms present new perspectives, their implementation within China's regulatory and governance landscape requires further exploration.

The case of Enning Road highlights the need for deeper research into the intricate balance between historical preservation and adaptive reuse, particularly in urban contexts where diverse stakeholder interests and development pressures intersect. This case study contributes uniquely to the discourse on heritage-led urban development, especially within the backdrop of China's rapid urbanization and evolving governance structures. While previous research has examined heritage as a foundation for urban development, the Enning Road case provides practical insights into the challenges and opportunities of aligning preservation efforts with economic viability and stakeholder engagement.

By offering a structured approach to identifying profitable functional uses within HBs, this study supports investors in making informed adaptive reuse decisions. Furthermore, it broadens the discourse on heritage-led urban development by identifying governance strategies that can facilitate sustainable adaptive reuse within China's dynamic urban landscape.

Data availability

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions

K.F. and Q.Y. wrote the main manuscript text. X.Y.and Y.W. prepared the figure and did the research. K.F. did the data analysis. Q.Y. drafted the manuscript. K.F. and Y.W. supervised and developed the manuscript. All authors reviewed the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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