

**Digital Modelling and Analysis of the Network Structure for Residential Historic Areas
in China**

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Abstract

Residential historic areas in China are crucial for urban fabric and cultural heritage. Given the complexity and dynamic nature of these areas, the conservation and renewal efforts demand precise spatial interpretation and effective methodological approaches. Under the hierarchical framework of typo-morphology, the network structure in discrete geometry is used to recognise the spatial pattern. Then a digital model is constructed, which calculates quantitative morphological indicators and clusters elements. This model enables real-time adjustments and feedback of the morphology and has been packaged as a software application. This study advances the scientific rigour and efficiency of the planning process and promotes it from 'the prediction based on human experience' to 'the precise evaluation based on data analysis'.

Keywords

Residential Historic Areas; Urban morphology; Network Structures; Digital analysis; Planning strategies

1. Introduction

1.1 Background

Many cities in China have long histories, and as a result, a large number of residential historic areas with different situations have been formed. Residential historic areas (RHAs) in this study mainly refer to a complete block with relatively old age, a certain scale, residential as the main function, and retaining the traditional Chinese low-rise residential and courtyard model (Pang et al. 2023). These historic areas are not only important components of the urban space but also important carriers of traditional culture in the urban area. As the most complex but necessary object in urban renewal, RHAs' conservation and renewal have become increasingly important issues, hence it is crucial to investigate digital modelling approaches and design strategies.

In the current urbanization process in China, planning and design work for urban renewal has already broken away from the simple mode of large-scale demolition and construction with the gradual popularization of the people-oriented design concept. The corresponding work mode has been shifted towards a more refined and focused direction on the traditional urban spatial pattern. In this process, qualitative analysis and decision-making methods make it difficult to form accurate value judgments when facing the complex built environment of RHAs. Therefore, it is necessary to systematically understand the overall spatial structure of historic areas and the characteristics of each micro unit, and based on this, the corresponding design strategies for each spatial element should be developed, so that differentiated conservation and renewal actions can be carried out.

However, residential historic areas in China have often undergone a long historical evolution. The street networks in historical areas have been constantly destroyed and redeveloped due to residents' disorderly construction of their own houses. The scope of each household's residential plot has also been repeatedly redefined with changes in property rights. Because of this historical process, RHAs often have an exceptionally complex structure composed of various spatial patterns. In addition, RHAs are not static objects, but dynamic material carriers that constantly change and develop along with government protection planning and residents'

independent updates. During the regeneration process, minor updates or constructions from a single sector, such as resident's properties or government's policies, may affect the spatial structure of the entire block. These changes have brought about a lot of repetitive analysis and redesign work.

Based on the above issues, we see that the conservation and renewal of RHAs in China should be guided by a detailed understanding of complex spatial structures. This is a process that takes micro units as the operating object, integrates multiple information and analytical results, and repeatedly formulates reasonable design strategies to achieve progressive work. On the one hand, a clear and accurate interpretive pattern is required. This pattern can accurately provide feedbacks to designer and planners with the overall spatial structure of RHAs and the detailed characteristics of each spatial unit in the complex environment. On the other hand, a more efficient and accurate system is also needed to provide the morphological analysis results of spatial units in real time to assist designers in making design decisions.

Therefore, in order to support and enhance the planning and design work of complex and dynamic environments in historic areas, this study intends to expand the existing form interpretation theory and construct a network structure analysis model that is in line with the current spatial relationship of RHAs in China. Subsequently, based on this network structure, the digital modelling of RHAs was achieved through autonomous programming technology, including the corresponding morphological analysis. At the same time, the methodology proposed by this research should be combined with the progressive and diachronic characteristics of the conservation and renewal of RHAs in practice. The real-time morphological analysis results can be provided during the dynamic evolution of the spatial environment, which can guide refined design decision-making work.

1.2 Literature review

1.2.1 Morphological interpretation research of historic areas

The morphological analysis of RHAs is based on the description and interpretation of its material space. After a long period of systematic research on urban morphology and its evolution, European scholars have gradually formed the Historico-geographical School represented by Conzen (Conzen 1960) and the Process Typological School represented by Muratori and Caniggia (Caniggia & Maffei 2001). The two schools of thought mutually confirm and form a complete system of typo-morphology. Subsequent scholars have continuously improved the interpretive patterns of typo-morphology, such as Kropf's multi-level theory, which integrates the views of the two schools of thought (Kropf 2014). Faced with the complex spatial environmental characteristics of RHAs in China, many researchers have begun to apply various interpretive methods involved in typo-morphology to the study of RHAs. Ji and Ding et al. applied the research method based on Nori maps to the old city of Nanjing and verified the similarities and differences between traditional urban space and modern urban space (Ji & Ding 2021). Dong et al.'s research focuses more on the combination of methods and practice. By drawing typological maps of different eras in the conversation and renewal of the Xiaoxihu Historical and Cultural Block, the evolution patterns of the block's spatial structure have been identified. Based on this, the targeted design of each property rights plot can be conducted

(Dong et al. 2019). Xia et al.'s research is more comprehensive. They analysed the typological characteristics of the block at multiple scales, from street texture to courtyard space, and then to detailed craftsmanship, in the conversation and renewal of the Kaiyuan Temple area in the old city of Bin County, Shaanxi Province. These characteristics were used as the main basis for the design of the block restoration (Xia et al. 2015). The current research demonstrates the feasibility and effectiveness of applying an interpretive system from the perspective of typomorphology to RHAs. This method can incorporate the complex and disordered spatial environment of RHAs into a relatively clear interpretive framework. However, current research has not been able to fully and effectively adapt to the large number of complex special situations in RHAs, and most methods mainly rely on manual work to complete a large amount of information sorting and graphic drawing. This process requires more effective methods to assist.

1.2.2 Technical Analysis Methods for Historic Areas

The interpretation and analysis of the morphology of RHAs is a complex process. Digital models can make up for the limitations of traditional statistics such as low reliability and slow computation in large-scale data processing, and suggest strategies for solving complex problems in morphological research. Ding and Ma interpreted the layout characteristics of traditional residential buildings in Anhui, Jiangsu, and Zhejiang provinces through spatial syntax, and conducted data clustering analysis using SPSS to explore the different usage patterns reflected by different residential spatial structures (Ding&Ma 2020). Dabbour used Depthmap to analyse the connectivity and visibility indicators of pedestrian movement in the old urban area of Damascus, the morphological characteristics of the urban road network in terms of accessibility have been quantitatively described (Dabbour 2021). Huang et al.'s research used 23 indicators from multiple dimensions such as "physical space vitality", "network space vitality", and "emotional level" to define the vitality characteristics of historic areas and evaluated them using the random forest algorithm. The corresponding methods were written in Python. (Huang et al. 2022). Wang et al. introduced deep learning methods in the study of village morphology and used algorithms written in Mathematica to represent images of over 6000 traditional villages in binary, thereby converting their morphological features into feature vectors. Finally, cluster analysis was performed on the feature vectors to reveal the type patterns of traditional village spaces (Wang et al. 2023). Cai et al. proposed a hybrid data-driven approach to support urban morphological quantification and multi-dimensional similarity analysis, using high-dimensional feature vectors (HDFV) extracted by a deep convolutional neural network (Cai et al. 2021). It can be said that whether based on existing analysis platforms or through programming to build corresponding method systems, digital methods have demonstrated accuracy and efficiency that manual statistical and analytical methods cannot achieve. In the early research process of conservation and renewal of historic areas, it has become a mature method to select appropriate digital technology means to achieve efficient and accurate rapid analysis of problems.

2. Construction of network structure of residential historic areas in China

2.1 General hierarchical structure of the residential historic areas

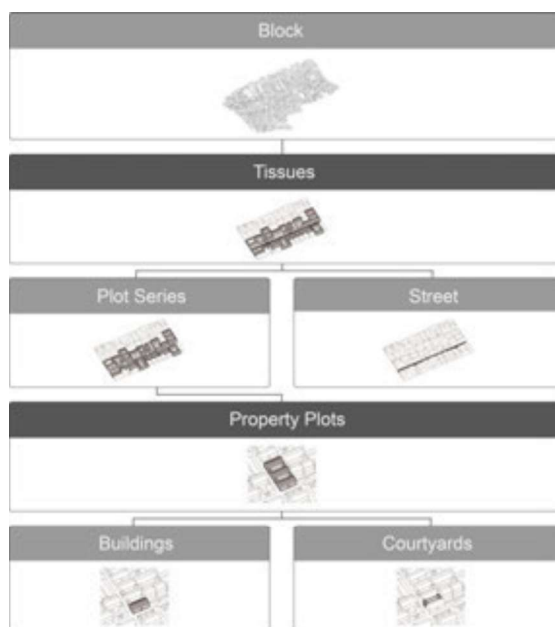


Figure 1. The hierarchical structure of components in residential historic areas in China

The description and analysis of the complex built environment of RHAs is the start point of design work. The scale hierarchy structure in the field of typo-morphology provides a clear descriptive framework for the spatial environment of RHAs, which can connect scattered and multi-class spatial elements into a whole. Based on the combination hierarchy theory of Kropf (Kropf 2014), the interpretive pattern in this study employs the hierarchical structure of ‘block-tissues-street and plots series-property plots-buildings and courtyards’ to recognize and identify the spatial structure of RHAs (Figure 1). The entire block is often connected by a complete road network, and the plots which are divided based on the evolution of property rights are the basic living units of residents. Therefore, the “simple tissue” composed of each road and its two sides connected in a fishbone shape becomes the basic element of the neighbourhood. Within the plot, traditional Chinese housing often presents a multi-courtyard pattern, with entrances and exits mainly located on the short side of the plot. Therefore, buildings and courtyards become the most basic spatial units. In this hierarchical structure, roads, plots, buildings and courtyards are the three most closely related levels to design, and their spatial characteristics will become the direct focus of this study.

2.2 Spatial complexity of the residential historic areas

Typo-morphology originated in Europe, where many cities often have relatively regular spatial patterns and the boundaries of plots are completely occupied by building facades (Figure 2). So the spatial status can be accurately reflected by a regular hierarchical structure. However, the

RHAs in China are different. On the one hand, due to the limitations of traditional building materials, low-rise brick and wood structure houses often cannot maintain a constant state for a long time. Therefore, most of the residential buildings in the blocks have undergone multiple demolition and reconstruction during their use (Pezzetti 2019). Each reconstruction will make corresponding adjustments based on the property rights and site conditions at that time. This process will not only change the spatial pattern inside the plot but also affect the overall road network spatial structure of the block. On the other hand, in just the past few decades, Chinese residential property rights policy has undergone multiple adjustments, resulting in plots being reclassified multiple times with changes in property rights (Dong et al. 2019). Its morphology has already broken the 'one-way entry, multiple courtyards' pattern which formed during the initial construction (Figure 3). The access and use methods of many plots are far from their actual layout patterns. The above two aspects together contribute to the spatial complexity of RHAs, which contains various special situations that cannot be directly identified using existing hierarchical structure theory.

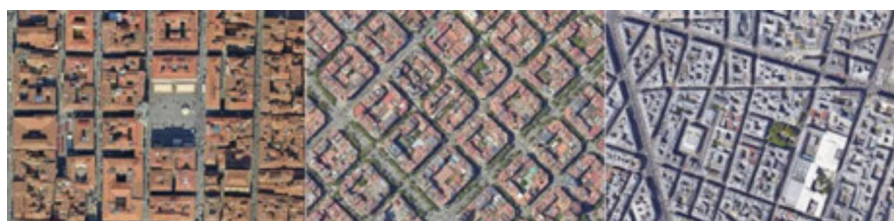


Figure 2. The spatial patterns of three European cities: Florence (left), Barcelona (middle) and Paris (right).

Based on the spatial relationship between roads, plots, buildings, and courtyards, four special situations of spatial structure within RHAs can be identified: interlocking, overlapping, co-inflection, and a composite condition termed the superposition state integrates these three configurations (Figure 4). Interlocking means that the same plot is connected to multiple roads and belongs to multiple tissues. Co-inflection is reflected at a more subtle level, that is, the same building or the same courtyard belongs to different plots due to the continuous division of property rights (Kropf 2014). Overlapping is relatively common in China's RHAs, that is, the plot is not directly adjacent to any road and must be reached through surrounding plots. (Song et al. 2024). The above three types of special situations often do not appear independently, but often co-occur in the same block or even the same plot. This also leads to the need to establish a more refined spatial relationship description system based on the hierarchical structure so that the morphological characteristics of each subtle element can be accurately reflected.

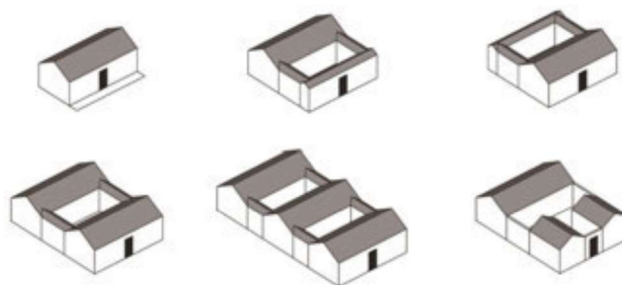


Figure 3. Typical layouts of traditional Chinese residential building groups including buildings and courtyards

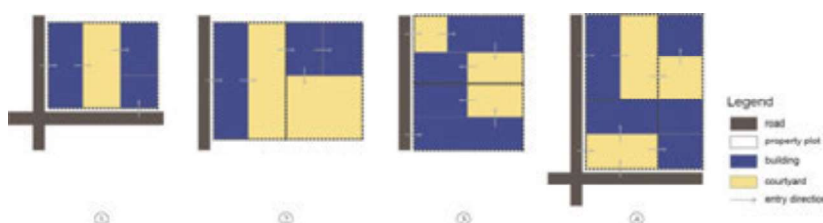


Figure 4. Illustration of 4 special situations of spatial structure within residential historic areas: (1) Interlocking, (2) Overlapping, (3) Co-inflection, (4) The superposition state

2.3 Access Network Structure of Residential Historic Areas

RHAs are generally based on a multi-scale hierarchical structure and contain a large number of complex situations. Faced with this characteristic, this study attempts to introduce graph theory models from the field of discrete geometry into morphological analysis. Under this model, the spatial elements and their connection relationships at multiple levels in RHAs will be abstracted into a network structure diagram composed of ‘points’ and ‘lines’. Multiple quantitative indicators in spatial syntax theory are used to analyse the position of each ‘point’ (i.e., each spatial element) in the overall network, to clarify the relationship between spatial elements and the overall neighbourhood, as well as the interrelationships between spatial elements.

Firstly, in the road hierarchy, each road is abstracted as a ‘point’ in graph theory, and the connection between roads is abstracted as the ‘line’ (Figure 5). The quantitative indicators of road morphology are measured by three values: depth value, connection value, and the proportion of connections with low-depth roads. The depth value refers to the minimum number of spatial conversions required for this road to reach the main roads outside the block. The depth value of the main roads outside the block is defined as 0, and the other roads are calculated progressively in sequence. The connection value refers to the number of other roads connected to this road, which reflects the connecting role that a certain road plays in the entire road network. The proportion of connections with low-depth roads reflects the degree of

commonality of the road relative to other surrounding roads. The calculation method is as follows: the number of roads connected to a certain road is A, the number of roads with lower depth values than this one among these roads is B, and the proportion of low depth value connections is B/A . The above three values can accurately define the position of any road in the road network, they can fully reflect the public and connectivity of a road.

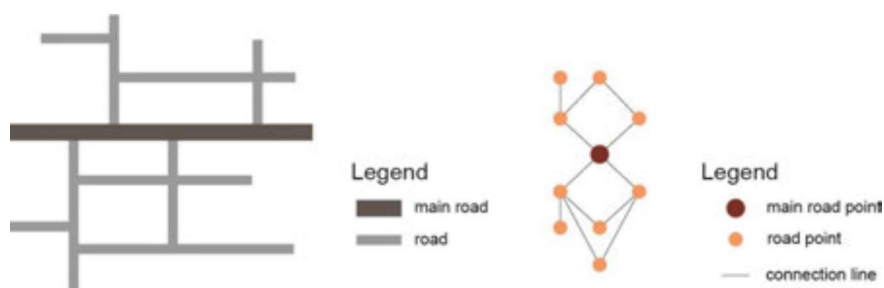


Figure 5. An example of extracting access network structure (right) based on a road-wise morphology instance (left)

In addition, in the plot hierarchy, the plots are abstracted as another set of 'point line' systems attached to the road network. Among them, 'points' represent various plots, and 'lines' represent the connection between plots and roads, as well as the connection between plots (Figure 6). The quantitative indicators of the plot's morphology are measured through external depth values, external connectivity values, internal depth values, and internal connectivity values. The external depth value and external connection value refer to the depth value and connection value of the most public road that the plot can be directly accessed. These two values are derived from the road network and reflect the accessibility and convenience of reaching the plot through the road network. The internal depth value is the minimum number of spatial conversions to reach the plot from the road and reflects the degree of overlap of the plot. In this case, the road is defined as the start point with a depth value of 0. The internal connection value refers to the number of paths that can directly enter the plot, including entering from surrounding roads and surrounding plots. This value is a visual representation of the tightness of the connection between the plot and surrounding spatial elements. The above four values collectively reflect the position of a plot in the street network (i.e. the higher level) and the plot sequence (i.e. this level).

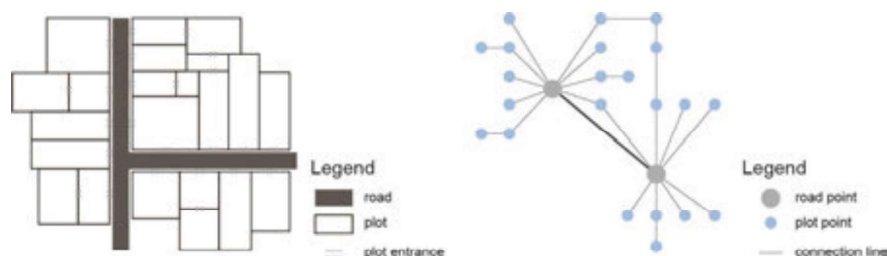


Figure 6. An example of extracting access network structure (right) based on a plot-wise morphology instance (left)

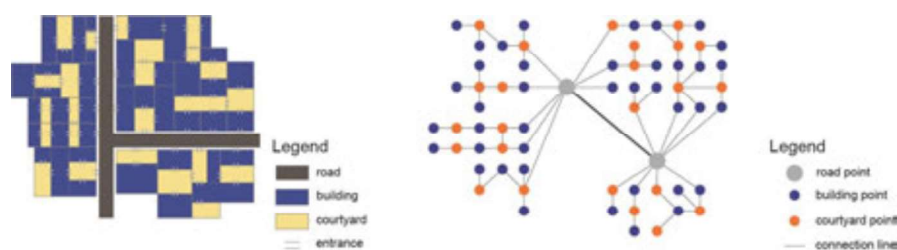


Figure 7. An example of extracting access network structure (right) with a focus on building-courtyard relationship from a morphology instance (left)

Finally, we focus on the hierarchy of buildings and courtyards. Due to the existence of various complex and special situations in RHAs, the access relationship between buildings and courtyards is significantly different from that of property plots. The division of property plots often completely breaks the spatial form of courtyards. Therefore, in order to conduct in-depth research on the position and interrelationships of each building and even each courtyard in the entire block, we need to build an independent ‘point-line’ network system outside of the property plots. The ‘point-line’ network system of buildings and courtyards is also attached to the road network. Buildings and courtyards are represented by different ‘points’, and ‘lines’ represent the connection relationship between buildings and courtyards and their connection relationship with roads (Figure 7). The quantitative indicators of the form of buildings and courtyards are also measured through external depth values, external connection values, internal depth values, and internal connection values. The calculation method for external depth values and external connection values is the same as the calculation method for plots. The internal depth value is also the minimum number of space transformations to reach the building or courtyard with the road as the starting point of the 0 depth value. The internal connection value refers to the number of paths that can directly reach the building or courtyard, including entering from surrounding roads and from adjacent buildings or courtyards. This value reflects the degree of tightness between the building or courtyard and the surrounding spatial elements. The above four values can also be used to measure the position of the building or courtyard, the most basic spatial element, in the overall network.

After the above process, we have preliminarily constructed an interpretation, representation and evaluation system based on a multi-scale hierarchical structure as the basic framework. In this system, the network structure diagrams have been used to define the connection relationships between spatial elements, the public and connectivity of spatial elements are accurately measured in the network through quantitative indicators. This system can accurately describe the complex spatial conditions of RHAs, and has a clear logical framework and quantifiable measurement methods, making it very suitable for simulation and reproduction through program algorithms.

3. Digital analytical modelling methods and their applications

3.1 Digital analytical model based on the hierarchical structure

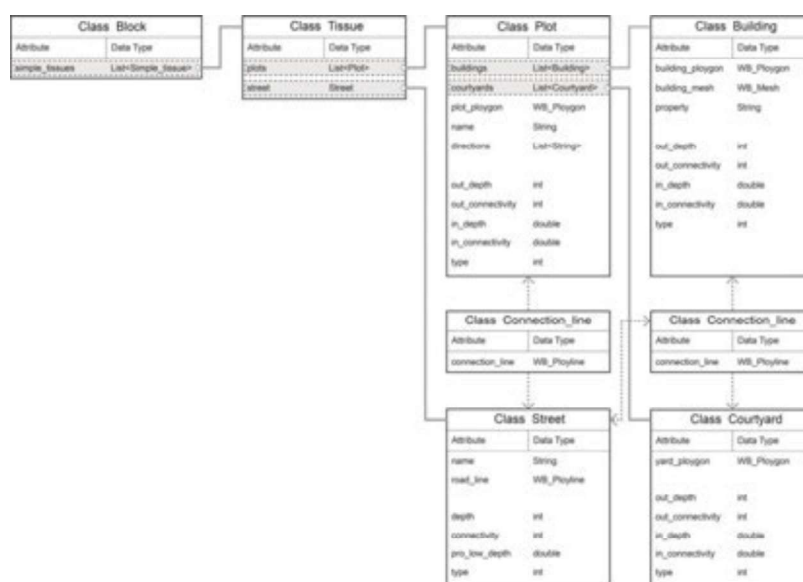


Figure 8. The structure of the digital model

Based on this multi-scale hierarchical network structure, this study constructed a corresponding digital analytical model through Java programming, allowing real-time RHA morphological structure analysis and interactive user interfaces. This model takes the basic class and object structures in the Java language as the main underlying logic, and constructs different classes for spatial elements (i.e., ‘points’ in the network structure diagram) and connection relationships (i.e., ‘lines’ in the network structure diagram) at multiple levels. At each level, information on all spatial elements is stored through a dataset containing all objects of that class. The quantitative feature values of each spatial element, the spatial elements of the next level which are contained within them, and their related connection lines are all included in the attributes of each object (Figure 8). At the same time, the various datasets in this digital model are not fixed entities, and the attributes of objects of each class are interconnected. Various datasets can also

be added or reduced at any time. These settings provide an algorithmic basis for the real-time completion of morphological analysis in the progressive conservation and renewal process of RHAs.

In order to have quick feedbacks of the morphological analysis for spatial elements at various levels, we translated the quantifiable feature values and the corresponding calculations from the network structure into mathematical or geometric algorithms, and then we implemented those in our interactive digital analytical model. Whenever the dataset of objects at each level is updated, the program can call the corresponding algorithm to recalculate the quantified values linked in the attributes of each object, thereby the temporal morphological analysis work in the RHAs progressive change process can be completed.

However, the complex quantitative indicators are still not intuitive enough and are difficult to directly guide the design. Hence the clustering algorithms have been introduced into the analysis framework of the program. This study incorporates the K-Means clustering algorithm into the digital model. After each update of the morphological quantification values, spatial elements at each level will be clustered based on the quantification values, the commonality and connectivity of spatial elements in the overall network can be reflected by clear type characteristics. Based on such type characteristics, the planning and design strategies can be referenced from similar cases. It should be noted that the weights of various quantitative indicators of spatial elements in the clustering process are adjustable to match the diverse needs. Users can obtain biased clustering results according to design needs to develop more targeted design strategies.

3.2 Add a front-end interface to form an analytical technology platform

After the construction of the digital model, it is necessary to build a matching front-end interface based on the designer's real-time need to obtain corresponding analysis results according to the updated site status or design adjustments in actual work. The front-end interface is a path for human-computer interaction with digital models. It is mainly used by designers and should be able to reasonably collect users' adjustments to multi-level spatial structures. Within the digital model, this interface should be linked to the backend data structure and algorithms. On the one hand, it should be able to visualize the necessary information in the digital model in real time. On the other hand, it needs to provide real-time feedback to the user's operations in the digital model and update the datasets at all levels.

This interface is based on the overall map of the block, which can visually display the spatial elements on multiple levels within the block, and indicate their type characteristics with colours. It can also display the network structure of points and lines between various spatial elements, allowing users to intuitively identify the entry relationship of the entire block. On the right side of the interface is the data display bar, which can display the overall form analysis results of the block in real-time. This interface has a detailed information query function. Users can click on any spatial element, and its detailed morphological information can be displayed in the data bar on the right (Figure 9). In order to meet the needs of users to obtain multivariate analysis results, the interface also has multiple display modes. Users can view separate analysis maps of spatial

elements at different levels at any time as needed and can adjust the view to three-dimensional for easier observation (Figure 10).



Figure 9. The analysis map and information bar in the user interface, where users can view detailed information of a certain plot (top) or detailed information of a certain building (bottom)

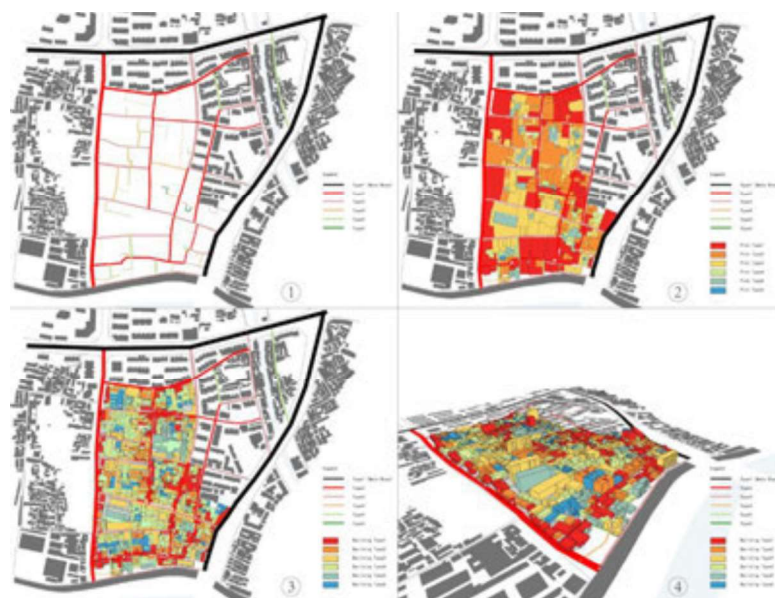


Figure 10. Multiple display modes for analysis map in the user interface, including analysis map of roads (top-left), analysis map of plots (top-right), analysis map of buildings (bottom-left) and 3D analysis map of the buildings (bottom-right)

The diachronic storage, recording, updating, and reanalysis functions are the core requirements in the conservation and renewal of RHAs, and they are also the core functions of our digital model. In the front-end interface, the operation panel is located on the left side of the interface, and users can directly modify spatial relationships at multiple levels on the block map through simple operations (Figure 11). One main mode of operation is to adjust the spatial elements themselves, including adding or removing roads, redefining plots, demolishing buildings, etc. Any operation will directly change the dataset of spatial elements. Another operation mode is to adjust the connection relationship between various spatial elements, users can add or subtract the connection lines between each element at any time to change the network structure of the block (Figure 12). Any modification is operated by the user within the interface based on the autonomous updates of residents in the neighbourhood or the active design of the designer. The digital model can provide new analysis results in real-time based on any modification, thereby providing feedback in real-time during the dynamic and gradual change process of RHAs. At the same time, the model also has the function of information export and storage. Users can export any state of the block and the analysis results in that state in various forms during the adjustment process, including exporting JPG format images of the analysis overall map, exporting Excel lists of various spatial elements and their corresponding morphological analysis results, and exporting dxf files including block topographic maps and corresponding analysis result layers. Through this mechanism, users can store the status of each stage in the design

adjustment process and conduct comparative analysis to find better planning and design strategies.



Figure 11. The complete user interface of the digital analytical model



Figure 12. Users can operate data by adding or removing roads (left), redefining plots (middle), and adding or subtracting the connection lines (right) through the digital analytical model.

3.3 Application Trial and Feedback

In order to facilitate the usages for planning designers in practical work, this digital model is packaged into an exe running program through exe4j. Then the relevant files of the program and the running environment are combined into an installation package through Inno setup. This digital model has been developed into an analytical technology platform that can be installed on any computer. The study is based on the actual conservation and renewal work of multiple RHAs (including Xiaoxihu, Diaoyutai, and Hehutatang) in the southern area of Nanjing.

Multiple planning designers were invited to test the value and shortcomings of the analytical technology platform based on the actual workflow.

During the trial process, this analytical platform demonstrates the effectiveness of assisting the planning and design phase of the RHAs' conservation and renewal through digital methods. Users can intuitively obtain detailed morphological analysis results of each spatial element, which serve as the main basis for obtaining design strategies. Quantitative indicators and clear type characteristics are used to guide planning and design work. This technical path makes up for the ambiguity of manual judgment and enhances the scientific nature of the design results. At the same time, the analytical platform has greatly reduced the repetitive analysis work caused by complex and dynamic spatial structures, which effectively improves work efficiency.

However, the designers involved in the trial also pointed out some limitations of the analytical platform. Firstly, in the conservation and renewal design process of RHAs, diachronicity is a very important concept. Although the current analytical platform takes into account the storage and export of analysis results at each stage, it does not form a historical operation path in the platform that can be rolled back, viewed and called at any time, so it cannot fully match the actual work needs. Meanwhile, current platforms can only provide morphological analysis of complex spatial environments from the perspective of network structure. In practical work, various constraints and problems should be considered in the conservation and renewal of historic areas. The platforms have not yet been able to overlay and analyse more information. Finally, this platform can essentially only complete morphological analysis work, it mainly targets the pre-design analysis and strategy acquisition stage. Therefore, the process from design strategy to actual design scheme generation still needs to be manually completed by designers, and technical methods have not yet penetrated the entire process from analysis to design.

4. Conclusion

In the field of planning and architecture, morphological design often relies on morphological analysis (Han 2013). Morphological analysis can reveal the objective laws of the spatial environment and provide early guidance for morphological design. This study applies data-driven techniques to the conservation and renewal of residential historic areas in China. A hierarchical network structure model is used to recognize the complex and dynamic multi-level spatial environment of the block, and accurate morphological analysis results are obtained in real-time to assist design decision-making. This research reflects the great potential of integrating digital methods in the planning and design process in complex spatial environments and involving multiple information, such as in RHAs in China. Digital methods can comprehensively analyse complex problems from a more quantitative and rational perspective, and provide accurate results in real-time. This research brings not only advancements in technical methods but also changes in working models. In this way, we can improve the planning process from 'the prediction based on human experience' to 'the precise evaluation based on data analysis'.

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