A machine learning method for predicting the spatial combination of community-embedded retirement buildings

Zhiqi WANG[1] , Yangpeng XIN[2] , Ying ZHOU[3] , Mingyu CHENG[4]

Abstract: Against the background of actively responding to population aging, the demand for community embedded retirement building construction is increasing daily. Given the density and complexity of urban built-up areas, renovating existing community buildings in the context of inventory renewal has opened up a practicable development path for retirement building construction. However, the contradiction between the spatial structure of existing buildings and the functional requirements of retirement buildings has become a difficult problem. The environment of urban communities in China is diverse and complex, and the traditional program that relies solely on architects or community managers to carry out the renewal design has the shortcomings of low efficiency and low utilization rate. In this paper, we propose a spatial combination prediction method for retirement buildings based on a Graph Convolutional Neural network (GCN), which realizes the prediction of spatial combinations of retirement buildings by using the GCN node classification task model and the generative design method under the constraints of the existing site environment. This study also takes the building room characteristics and room connectivity into consideration, which can reflect the building usage more realistically in model training and generative design optimization, and this method has significant advantages in both time efficiency and space utilization.

Keywords: retirement building; graph convolutional neural network; generate design; space combination

1 Introduction

China's aging population is rapidly increasing, making it a national priority to address this issue and provide basic elderly care services for all. This demographic shift has led to a sharp rise in demand for elderly care services, exacerbating the supply-demand gap. With the miniaturization of family size and rapid economic and social development, home-based elderly care is becoming less feasible. Consequently, community-embedded elderly care is emerging as a key direction for China's modern elderly care model *(Du and Ma, 2024)*, driving up the demand for such facilities. In dense urban areas, renovating existing community buildings offers a practical solution for developing retirement facilities.

However, the contradiction between the spatial combination of existing buildings and the functional needs of retirement buildings has become a significant challenge *(Li et al., 2024)*. In China's diverse and complex urban communities, relying solely on architects or community managers for renewal design is inefficient and results in low utilization. While some sustainable community and building renovation methods were discussed in studies—such as community renewal strategies based on "active aging" theory *(Han and Wang, 2023)*, decision support systems for residential building renovation *(Serrano et al., 2018)*, and the "middle zone" optimization design method for interior space of retirement buildings *(Wang et al., 2022)*, there remains a lack of effective methods to integrate retirement building spaces into the existing community spatial combination.

This paper proposes a graph convolutional neural network (GCN)-based spatial combination prediction method for retirement buildings, using the GCN node classification task model and generative design to predict spatial combinations under existing site constraints. GCN, an emerging deep learning model for graph-structured data, excels in analyzing and predicting complex graph-structured nodes but is less applied in ar-

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chitecture. In this model, the building spatial structure resembles a functional bubble graph, translatable into graph-structured data with node characteristics. Generative design, a key development in building digital technology, remains vital due to emerging optimization algorithms. This study considers existing site limitations, using generative design algorithms and graph structure optimization to predict feasible retirement building space combinations. It also accounts for building room characteristics and connectivity, enhancing the model's realism in usage prediction and generative design optimization, with significant advantages in time efficiency and space utilization.

The paper introduces the study's background and methodology, followed by a literature review on community embedded retirement buildings, community environment renovation, GCNs, and automatic floor plan generation design. It then details the technical methodology and findings, concluding with a discussion.

2 Literature Review

2.1 Community-embedded retirement building construction

With the aggravation of population aging and the diversified needs of the elderly, the construction of community-embedded retirement buildings is an important initiative to respond to the challenges of the aging society, meet the needs of the elderly for senior care services, and promote the innovation of senior care service models. Several studies have used case studies, field research, statistics, and modeling analysis to propose strategies related to the construction of community-embedded retirement buildings, such as Hu Huiqin et al. pointed out that converting residences into retirement buildings is an effective construction pathway through a field study of the background Chaoyang District's aging communities *(Hu et al., 2018)*, and Zhang Xinzhe et al., under the concept of CCRC, through a case study and statistical methods proposed a spatial construction framework of facility units, flexible organization and integrated implantation, and proposed a spatial configuration strategy of facility types, functional organization and allocation methods based on the research results *(Zhang et al., 2022)*. Some scholars have also studied the demand and satisfaction of community-based home care services through the Kano model analysis and AHP-fuzzy comprehensive evaluation method, and based on embeddedness theory, proposed tangible and intangible embeddedness modules based on the embedded theory *(Hong et al., 2023)*. The embedding method and scale of retirement buildings in urban established settlements need to be determined by community environment data *(Xing, 2023)*.

As architects and designers, urban small-scale embedded retirement buildings should meet the principles of operational logic and integration into the community, and establish the value standard of "people-oriented" *(Zhang and Zhao, 2017)*, and there is a correlation between the spatial combination of the retirement building and the living behaviors of the occupants *(Li and Li, 2011)*, so the research on the spatial combination of the retirement building should be emphasized. Focus on the study of the spatial structure of retirement buildings, which inspires this study. In addition, in the context of the rapid development of intelligent technology, intelligent design strategies have been gradually applied to retirement building design *(Bu et al., 2024)*. In this study, the new deep learning technology in the field of artificial intelligence guides the direction of the research problem, takes the spatial combination of retirement buildings as an important object of research, adheres to the value orientation of "human-centeredness", and promotes the theoretical progress of intelligent design strategies in the field of retirement building research.

2.2 Renovation of existing environments in the community

In the context of the era of inventory renewal, along with the aging of the population and the built environment of the community, the community environment and existing building renovation become more and more necessary. Professor Cheng Xiaoqing led a team to carry out the practice of aging-adapted renovation in the Beijing Dazhalan community in 2015 and put forward renovation suggestions and methods in combination with practical experience *(Cheng et al., 2018)*, and some scholars summarized that the replacement method, alteration method, and addition method are of guiding significance in the use of existing resources to adapt to the new functional needs *(Li et al., 2024)*. At the community level, the Kano model helped to explore the supply and demand of community elderly services and the design needs of community public spaces *(Lyu et al., 2024)*. Han Linfei et al. proposed a community renewal strategy based on the theory of “active aging”, which includes the reconstruction of spatial systems and the establishment of an integrated elderly management system *(Han and Wang, 2024)*. The community renewal strategy based on the theory of “active aging” was proposed by Han Linfei et al.

Traditional research methods, such as those based on the Kano model, undoubtedly have great potential, but the complexity of the work process and the multiple objectives of the research make it difficult to relate to the spatial design level. The research methodology in this paper focuses on architectural spatial combinations, making the theoretical approach operational and practicable.

2.3 Graph Convolutional Neural Networks (GCNs)

Graph data consists of nodes and edges, which can contain node features and edge weights, and is commonly found in fields such as social networks, recommender systems, biological information, etc. Graph convolutional neural networks are a class of deep learning models for dealing with graph data, which have received wide attention in recent years and have been widely used in computer vision, biochemistry, natural language processing, and recommender systems, etc. *(Liu et al., 2023)*. As a powerful tool for analyzing graph data, graph convolutional neural network has obvious advantages in node classification, graph classification, edge prediction, etc. In the field of architecture, some scholars provided an efficient solution for beam layout design of frame structures by using graph convolutional neural network based on the topological characteristics of beam-column connections of frame structures, and the model prediction results are not much different from the design results of structural designers *(Zhao et al, 2023)*. The adjacencies of different rooms in a building were difficult to summarize in a nutshell, and a method proposed to extract the spatial topology from BIM and represent it as a graph, and in turn, utilized a subgraph matching algorithm to achieve fast querying in the early stage of design *(Langenhan et al., 2013)*. In this paper, we refer to and simplify such topology graphs and utilize GCN to perform convolution operations and feature extraction on them.

2.4 Automatic floor plan generation design

With the improvement of computing power and the development of artificial intelligence technology, architectural generative design gradually plays an important role in the field of digital architecture, especially in the automatic generation of architectural floor plans to highlight the charm. Weber Ramon Elias et al. from MIT combed through the mainstream computerized architectural automatic layout methods and attributed the architectural automatic floor plan generation design methods to three categories: bottom-up, top-down, and referential *(Weber et al., 2022)*. For a long time, GAN algorithms were generalized for floor plan generation research. Cui Zhe et al. explored the learning effect of GAN generative models with different architectures on generating class floor plans *(Cui et al., 2023)*, and Liu Jiepeng et al. applied GAN algorithms to functional floor plan generation of a specific type of building using knowledge graphs *(Liu et al., 2024)*, the retirement building floor plan is functionally diverse and complex, the GAN algorithm has not been able to be applied to the design of automatic floor plan generation for retirement buildings.

Hua Hao proposed a mathematical method *(Hua, 2016)* to understand the building floor plan layout as two parts: independent rooms and relationships between rooms, focusing on the irregular shape assessment of each room and the neighboring relationship between each pair of rooms, which provides the idea revelation and theoretical support for the progress of the generative design phase of this study.

3 Methodology

In this study, we propose a spatial combination prediction method for community-embedded retirement buildings using deep learning (GCN) and generative design, as shown in Fig. 1. Using real community retirement building plans as the database and research object, we first depict the dataset with Rhino and observe the spatial combination characteristics. Grasshopper is used to extract features from the dataset, and the Random Forest Algorithm classifies the standardized node features. We then build a graph convolutional neural network model for node classification. Finally, using the trained GCN model combined with a genetic algorithm, we predict the spatial combinations of retirement buildings within existing building plans.

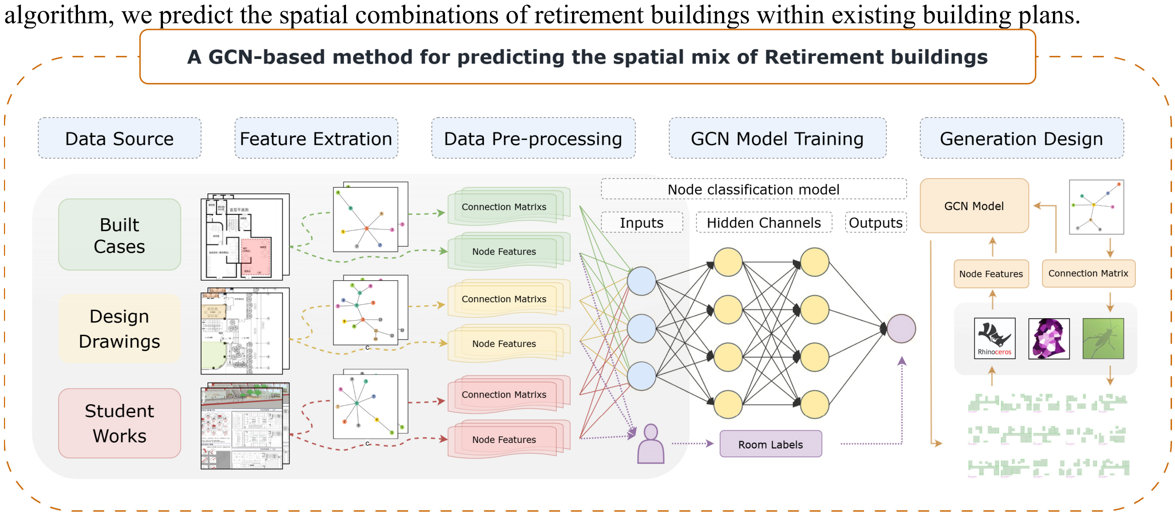


Fig. 1 The technical framework of this study, self-drawing.

3.1 Data acquisition and pre-processing

To enhance the generalization ability of the graph convolutional neural network model, ensuring dataset diversity is essential. We collected 39 building plans from various sources, including community-embedded retirement buildings, community home care service facilities, community daycare centers, and student works in retirement communities. Through Rhino and Grasshopper, the area, perimeter, and coordinates of rooms were obtained, along with data on room connectivity, Table 1 shows some of the data we acquired.

Index	Source	Area	Perimeter	X	Y	Connection	Type
1	18(Built Case)	20.67	18.98	-12.48	-5.45	3,7	5(Bedroom)
15	17(Built Case)	6.79	16.30	12.40	1.76	19	4(Service)
320	6(Student Work)	4.79	8.80	39.62	-17.20	324	4(Service)
543	2(Student Work)	48.79	28.18	1.32	-14.45	547	3(Activities)
938	27(Design Plan)	105.58	46.39	21.45	-2.98	934,945	1(Public)
1111	31(Design Plan)	29.58	23.07	10.78	-45.83	1119	3(Activities)
1339	22(Design Plan)	178.38	103.24	-2.74	-3.85	X	2(corridor)

Table 1 Sample dataset, self-drawing.

In building plans, "doors" signify traversal between spaces. Rooms are represented as nodes with features, and connections or doors between rooms are edges, effectively described by an adjacency matrix. The datasets in this study, derived from existing retirement building plans, are free from missing or outlier points. Feature engineering explored correlations between room features, types, and connectivity, revealing high correlations between room area, shape, and type. "Compactness," describing how closely a shape resembles a circle, was selected along with area as characterization data. Robust normalization was used to preprocess room area and compactness to mitigate the impact of extreme values.

To increase the dataset diversity and ensure the model training effect. We perform data augmentation on the existing 39 graph data. In architectural design, room-to-room connections are specific, foyers can be connected to corridors but are rarely connected to bedrooms. Assuming that corridor A1 is connected to bedroom A2 in graph A, and that corridor B2 is connected to bedroom B2 in graph B, then we assume that it holds that

A1 is connected to B2 in diagram C. Using this permutation method, we expand the original 39 graph data to 117, and participate in graph convolutional neural network training together.

3.2 Graph Convolutional Neural Network Model Building

Graph Convolutional Neural Networks (GCNs) excel in node classification by aggregating neighboring features. The GCN model construction starts with data preparation, obtaining the node feature matrix and edge index. The node feature matrix contains each node's feature vector, while the edge index describes node connectivity. The model comprises multiple graph convolution layers, updating node features based on neighboring node information.

In this method, each layer's node features incorporate information about both the node itself and its neighbors. We build a three-layer graph convolutional neural network (GCN) to capture the graph's complex relationships more effectively. Initially, a random forest algorithm evaluates the impact of features on node classification, calculates the weights for each feature, and multiplies these weights with the node features before feeding them into the convolutional layer.

Each graph convolutional layer's output features serve as the input for the next layer, with the final layer's output used for classification. During forward propagation, node features and edge indices are input into each graph convolution layer, followed by a ReLU activation function to generate updated node representations. The Adam optimizer adjusts each layer's parameters via backpropagation to minimize discrepancies between model predictions and true labels. The training process includes validation steps to monitor model performance, prevent overfitting, and adjust hyperparameters.

Node and edge indices are mapped and filtered to ensure only the correct training, validation, and test data are used. The ultimate goal is to achieve good classification performance on unseen test data through iterative training and validation. Key aspects of the model-building process include node feature updates, information aggregation in each graph convolution layer, parameter optimization, and performance evaluation during training, as illustrated in Fig. 2. These components together form an end-to-end GCN model.

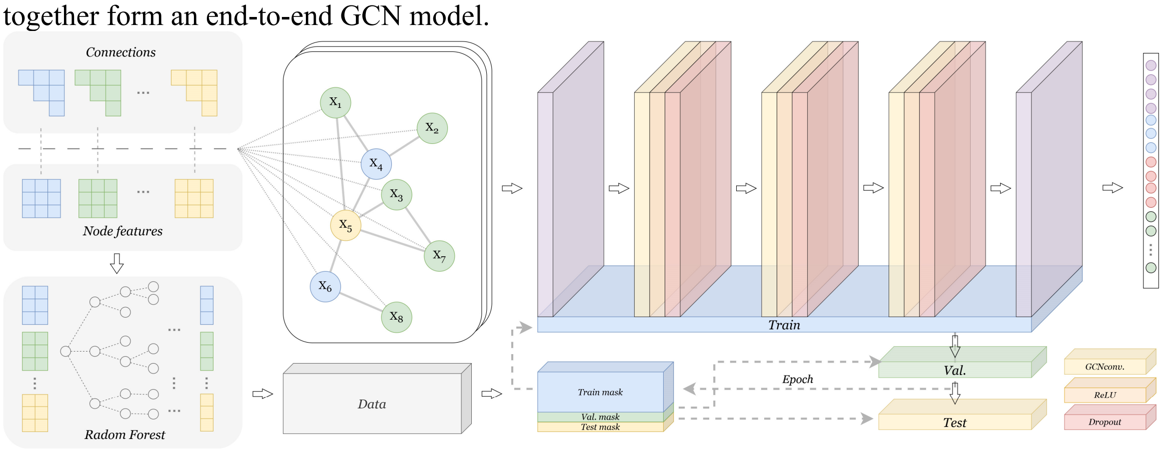


Fig. 2 GCN-based model architecture for node classification, self-drawing.

3.3 Design of spatial combination plan generation for retirement building

Automatic floor plan generation design with room adjacencies as a condition *(Hua, 2016)* is a method that can be developed among retirement buildings. In this study, the floor plan layout of the building is divided into two parts: individual rooms and relationships between rooms. The focus is on evaluating the characteristics of each room and the adjacencies between pairs of rooms. Using image patterns, the program generates various layouts that satisfy the user's geometric and topological requirements.

The user inputs the spatial layout of the existing building plan and the expected adjacencies, and the program calculates the topological cost by comparing the adjacencies between the desired adjacencies and the actual areas. This work is based on the Rhino platform and grasshopper programming and is implemented using a Genetic Algorithm through Wallacei, which evaluates the geometric feature cost of each room by the GCN model that has been trained to take into account the shape and size of the room. Finally, the floor plan layout solution that best meets the desired conditions is filtered. Fig. 3 illustrates a programming scheme based on Rhino, Grasshopper, and Wallacei that sets a random seed for the selection of an existing graph.

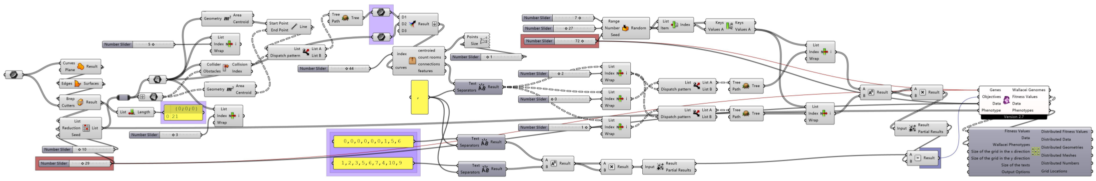


Fig. 3. A Grasshopper-based implementation approach, self-drawing.

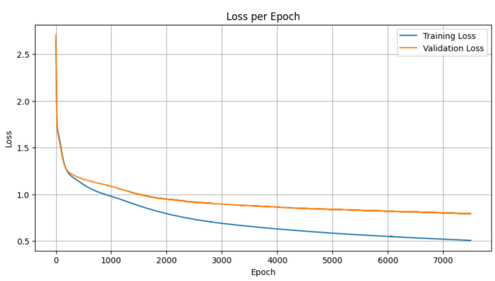
4 Results and discussions

This GCN model consists of three graph convolution layers, each of which updates the node representation by projecting node features into a new representation space and aggregating information from neighboring nodes. Each graph convolution layer is followed by a ReLU activation function to enhance the nonlinear modeling capability of the model. The model uses the Adam optimizer to optimize the model parameters with a learning rate of 0.0005, while L2 regularization (weight decay) is applied to control the model complexity.

After about 7 thousand epochs of training, the model has a final loss of 0.50 on the training set and 0.78 on the validation set, which indicates that the model can effectively learn the features of the data during training and performs well on the validation set, albeit with some fluctuations. Finally, on the unseen test data, the model has a test accuracy of 0.80. This result shows that our model maintains good classification performance even when dealing with new data, thus validating its generalization ability and usefulness.

We further analyze the training process of the model by plotting the image of the loss function with epoch. Fig. 4 shows that the training loss and validation loss gradually decrease with the training process, and the validation loss also exhibits some fluctuations, but the overall trend remains consistent.

```
class Net(torch.nn.Module):
    def __init__(self, in_channels, hidden_channels_list, out_channels, dropout=0.5):
        super(Net, self).__init__()
        self.layers = torch.nn.ModuleList()
        self.layers.append(GCNConv(in_channels, hidden_channels_list[0]))

        for i in range(1, len(hidden_channels_list)):
            self.layers.append(GCNConv(hidden_channels_list[i-1], hidden_channels_list[i]))

        self.layers.append(GCNConv(hidden_channels_list[-1], out_channels))
        self.dropout = dropout

    def forward(self, x, edge_index):
        for layer in self.layers[:-1]:
            x = layer(x, edge_index).relu()
            x = F.dropout(x, p=self.dropout, training=self.training)

        x = self.layers[-1](x, edge_index)
        return x.log_softmax(dim=-1)
in_channels = data.x.size(1)
hidden_channels_list = [16,32,64]
out_channels = data.y.max().item() + 1  # +1 because class indices start at 0

model = Net(in_channels, hidden_channels_list, out_channels, dropout=0)
optimizer = torch.optim.Adam(model.parameters(), lr=0.0005, weight_decay=1e-4)
criterion = torch.nn.CrossEntropyLoss()
```



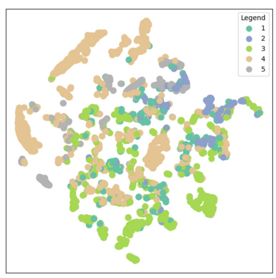


Fig. 4. Model definition, hyperparameter settings, loss function images, and training results, self-drawing.

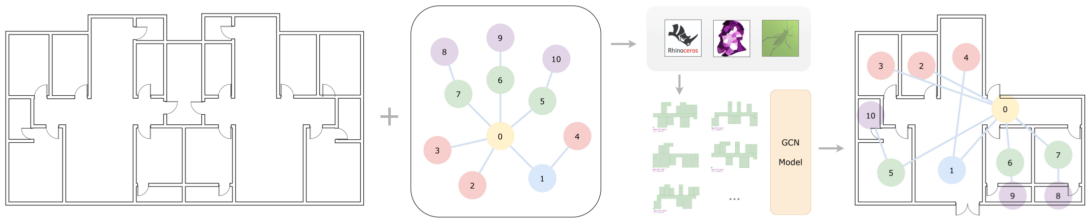


Fig. 5. An experiment in generative design, self-drawing.

We select the first floor plan of a building to be remodeled in a certain community, whose original function is residential, and conduct a generative design experiment on it using the method in this study. First of all, the user wants to build a small community-based home care service center, which contains about 11 rooms, and the types of rooms and connectivity relationships are represented as a graph. We import this requirement and the existing building plan into the generative design program, which proposes several possible scenarios for the user, filters the expected scenarios by using adjacency relationships and the GCN model and ultimately selects the one that best fits the user's requirement. We develop the choice and get the design result as shown in Fig. 5.

In the past, graph convolutional neural networks have been widely used in computer vision, biochemistry, natural language processing, recommendation systems, etc., while in the field of architectural design, this novel neural network technique has not been emphasized by researchers. This study incorporates the graph convolutional neural network approach into the exploration of architectural design, which is innovative at the theoretical level.

5 Conclusions

This paper proposes a spatial combination prediction method for community-embedded retirement buildings, using a mature retirement building floor plan layout scheme as the dataset and applying graph convolutional neural networks for deep learning. It then employs a generative design method to predict reasonable floor plan layouts considering the constraints of the established community environment.

This study has some limitations: 1) Regarding the dataset, resource and time constraints led to dataset selection and production based on the researcher's experience, causing certain biases and contingencies. Despite using data enhancement methods, the dataset's number and diversity are somewhat lacking, affecting model generalization and accuracy. 2) Regarding visualization, the proposed method is a pre-design spatial layout approach, but due to energy and time constraints, it has not yet been developed into an end-user application for designers or community managers, requiring further optimization and experimentation for practical application.

The expansion of the dataset and the design of the software visualization are of great significance for the future application of this study. By introducing more fine-grained retirement building data and field research, the characteristics and patterns of the spatial layout of community-embedded retirement buildings can be captured more precisely.

Future research will explore and innovate in the application of deep learning methods for architectural spatial assemblage, improve the design efficiency of community recreational facilities, and develop software visualization tools to contribute to the effective construction of community recreational facilities and the sustainable development of China's aging society.

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References

1. Bu, D. Q., Zhang, L., & Jiang, L. (2024). Intelligent research on community home care service facilities. Intelligent Buildings and Smart Cities, 5, 155-157.
2. Cheng, X. Q., Zhang, H. X., & Yin, S. Z. (2018). Community practice of aging-adapted renovation of existing buildings: insights from the construction of a community retirement service station in Dazhalan, Beijing. Journal of Architecture, 8, 62-67.
3. Cui, Zhe, Guo, Yu, & Li, Hua. (2023). A pix2pix-based method for generating and evaluating class plans. Residential Science and Technology, 43(9), 27-35.
4. Du, Peng & Ma, Qifeng. (2024). Community-embedded elderly care in China: An analysis of the current situation and problems. Population and Development, 30(3), 113-124.
5. Hong, Jianming, He Yao, & Long, Liangchu. (2023). A Study on the Demand and Satisfaction of Community Home-Based Elderly Services Based on Embeddedness Theory: A Case Study of a Community in Guilin City. People's City, Planning for Empowerment - Proceedings of the Annual Conference on Urban Planning in China 2023 (19 Housing and Community Planning), 16.
6. Han, L., & Wang, B. (2023). Research on the Community Renewal of "Active Adaptation to the Elderly" in the Unit Compound. Proceedings of ECSF 2021 (1–14). Springer International Publishing.
7. Hu, H., Xu, Z., & Che, G. (2018). A methodological exploration of converting residences into residential care facilities for the elderly in old communities—A case study of Chaoyang District, Beijing. Journal of Asian Architecture and Building Engineering, 17(3), 409–416.
8. Hua, H. (2016). Irregular architectural layout synthesis with graphical inputs. Automation in Construction, 72, 388–396.
9. Intelligent floor plan design of modular high-rise residential building based on graph-constrained generative adversarial networks. (2024). Automation in Construction, 159, 105264.
10. Li, B. & Li, Q. L. (2011). A Comparative Study of Spatial Structure and Expansion of Living Behavior in Senior Living Facilities. Journal of Architecture, S1, 153-159.
11. Li, S.J., Jia, Y.Y., & He, W.J. (2024). A study on the strategy of converting existing buildings into retirement buildings in urban communities under the background of inventory renewal. Architecture and Culture, 2, 157-159.
12.Liu, J. Q., Tu, W. X., & Zhu, E. (2023). A review of graphical convolutional neural networks. Computer Engineering and Science, 45(8), 1472-1481.
13. Langenhan, C., Weber, M., Liwicki, M., Petzold, F., & Dengel, A. (2013). Graph-based retrieval of building information models for supporting the early design stages. Advanced Engineering Informatics, 27(4), 413–426.
14. Liu, J., Qiu, Z., Wang, L., Liu, P., Cheng, G., & Chen, Y. (2024). Intelligent floor plan design of modular high-rise residential building based on graph-constrained generative adversarial networks. Automation in Construction, 159, 105264. https://doi.org/10.1016/j.autcon.2023.105264.
15. Lyu, L., Tang, H., & Wang, B. (2024). Research on the Renewal Design of Community Public Space Under the Smart Elderly Care Model. Proceedings of the 2023 International Conference on Green Building, Civil Engineering and Smart City (875–891). Springer Nature.
16. Serrano-Jiménez, A., Barrios-Padura, Á., & Molina-Huelva, M. (2018). Sustainable building renovation for an aging population: Decision support system through an integral assessment method of architectural interventions. Sustainable Cities and Society, 39, 144–154.
17. Wang, H., Hou, K., Kong, Z., Guan, X., Hu, S., Lu, M., Piao, X., & Qian, Y. (2022). "In-Between Area" Design Method: An Optimization Design Method for Indoor Public Spaces for Elderly Facilities Evaluated by STAI, HRV, and EEG. BUILDINGS, 12(8), 1274.
18. Weber, R. E., Mueller, C., & Reinhart, C. (2022). Automated floorplan generation in architectural design: A review of methods and applications. Automation in Construction, 140, 104385. https://doi.org/10.1016/j.autcon.2022.104385
19. Xing, Zekun. (2023). Study on the Embedding and Scale of Elderly Service Facilities in Existing Urban Settlements--Taking Beilin District of Xi'an as an Example. People's City, Planning Empowerment - Proceedings of the Annual Conference on Urban Planning in China 2022 (19 Housing and Community Planning), 14.
20. Zhang, Song & Zhao, Ya. (2017). Research on the Design of Embedded Senior Living Facilities in Small Urban Communities. Journal of Architecture, 10, 18-22.
21. Zhang, Xinche, Liu, Conghong, & Yang, Hongwei. (2022). Exploring the spatial configuration of community-embedded elderly care facilities under the CCRC concept: Building a continuum of care community in Tianjin. Southern Architecture, 5, 73-82.

22. Zhao, P., Liao, W., Huang, Y., & Lu, X. (2023). Intelligent beam layout design for frame structure based on graph neural networks. Journal of Building Engineering, 63, 105499.