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Development of an Urban Rail Transit Line Design System Using 3D GIS-Integrated Building Information Modeling: A Case Study in Urban Traffic Optimization

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Abstract: The rapid pace of urbanization has exacerbated traffic congestion, necessitating innovative solutions to enhance urban mobility. This study presents a novel urban rail transit line design system leveraging a three-dimensional Geographic Information System (3D GIS) integrated with Building Information Modeling (BIM). The system integrates K-means clustering algorithms and GIS functionalities to generate optimized rail transit designs. Performance tests confirm the system's reliability and effectiveness, revealing significant advantages in design time, cost, and scientific precision compared to traditional methods. Notably, the system achieved 86% user satisfaction, though only 24% expressed willingness to adopt it, primarily due to cultural and implementation challenges. This research highlights the potential of combining GIS and BIM technologies for sustainable urban traffic solutions, while underscoring the need to address human-centric considerations for widespread acceptance.

Keywords: Geographic Information System; GIS Integrated Architecture; Information Model; Rail Transport Line

1. Introduction

With the rapid advancement of societal development, urban landscapes are undergoing unprecedented transformation. A surge in urbanization has led to the proliferation of high-rise buildings and a marked increase in population density. While such demographic growth and urban expansion bring economic and developmental benefits, they also impose significant challenges, particularly in urban transportation systems. The rapid rise in population has caused severe congestion within urban transportation networks, exacerbating the already limited capacity of road infrastructure and creating an urgent need for innovative and effective solutions to address these issues. The issue of urban transportation has attracted considerable attention from researchers worldwide, with diverse perspectives and proposed methodologies to mitigate these challenges. Gkiotsalitis Konstantinos emphasized the gravity of urban transportation problems, particularly during the COVID-19 pandemic, and highlighted the need for robust strategies to address the vulnerabilities of public transport systems during crisis situations [1].

Similarly, Tomasiello Diego Bogado advocated for comprehensive planning to fundamentally address urban traffic issues. His proposed multi-temporal transport network model aimed to enhance accessibility through detailed testing and evaluation [2]. Furthermore, Du Bowen underscored the role of scientific and technological interventions in tackling urban traffic challenges. He introduced the concept of a deep irregular convolutional residual short-term memory artificial neural network to predict passenger flow in urban transport systems. His experiments validated the model’s efficacy in forecasting traffic patterns [3]. Other researchers have also examined the multifaceted dimensions of urban traffic issues. Olmos Luis E presented a macro-dynamic theoretical perspective, warning of the potential collapse of urban traffic systems under current trends and substantiating his argument with extensive data and real-world examples [4]. However, a critical review of these studies reveals certain limitations. While they successfully identify key problems and offer theoretical frameworks, most of the proposed solutions lack practical implementation pathways and remain largely speculative. This gap underscores the need for solutions that are not only scientifically robust but also feasible for real-world application.

Through a targeted literature review, a subset of detailed and methodologically rigorous studies was identified for deeper analysis. For instance, Aletta Francesco developed a novel approach to assess urban traffic volumes by mapping noise emissions in Italy during COVID-19 containment measures. His method enabled the evaluation of traffic conditions and informed region-specific planning strategies [5]. Lu Qiong explored the impact of autonomous vehicles on urban traffic network capacity, employing microscopic traffic simulation experiments to analyze and demonstrate the implications of autonomous technology [6]. Osipov Vasiliy proposed a predictive model for urban traffic flow using a recursive neural network with a layered spiral structure, emphasizing the synergistic potential of network technologies and urban traffic systems [7]. Additionally, Lai Yongxuan suggested improvements to taxi travel routes based on Coulomb's law of urban traffic, demonstrating the benefits of optimized route planning for overall traffic efficiency [8]. While these studies provide scientifically validated and technically feasible approaches, a common limitation persists. Most research focuses on vehicle-centric solutions, aiming to optimize or enhance the performance of urban vehicles without addressing the broader structural and infrastructural issues inherent to urban traffic systems. This vehicle-focused perspective often neglects the potential of systemic interventions that could fundamentally alleviate urban transportation challenges.

To address this gap, this study proposes the development of an urban rail transit line design system based on a 3D Geographic Information System (GIS) integrated with Building Information Modeling (BIM). By incorporating rail transit into urban infrastructure, the proposed system aims to diversify transportation modes, thereby reducing the pressure on existing road networks. This system represents a shift towards a more holistic approach to urban traffic management, leveraging advanced technologies to optimize design and enhance urban mobility.

2. Clustering Algorithm GIS Theory and Method

After determining the basic direction of this paper, how to choose the design method has become the key issue of this design. The appropriateness of the method selection directly affects the overall performance of the system. Therefore, the design method needs to be considered in many aspects. In the data consulted, some people put forward the theoretical concept of convolutional neural network based on differential feature fusion for the construction of railway transportation. However, this method has poor applicability and does not meet the requirements of this design [9]. Some people also put forward the idea of establishing a model of urban traffic flow, believing that urban traffic can be understood through the model, so as to quickly deal with traffic problems and achieve the purpose of alleviating traffic pressure [10]. Although this idea is indeed in line with this design, there are still some problems in its method.

After analyzing and comparing a large number of documents, this paper decides to use K-means clustering algorithm as the core algorithm to build a three-dimensional GIS integrated building information model of urban rail transit line design system. The main work flow of urban rail transit line design system based on 3D GIS integrated building information model is as follows. The user first transmits the data to the design system. The design system calculates the data by clustering algorithm according to the transmission data, and the data calculated by clustering algorithm is divided into different clusters. Then, the geographic information system carries out the secondary identification and construction of the cluster data to form a complete set of urban building data model, and carries out the optimal planning analysis of the rail transit line within the data city model to give the optimal rail transit line. The flow chart of urban rail transit line design system based on 3D GIS integrated building information model is shown in **Figure 1**.

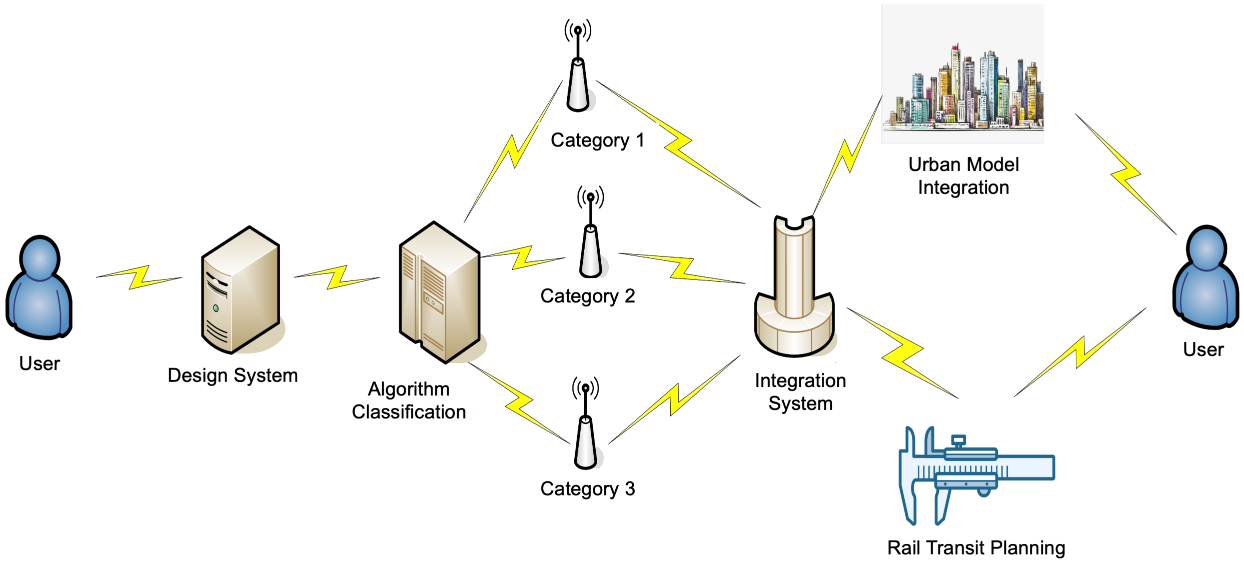

Figure 1. Workflow chart of urban rail transit line design system based on 3D GIS integrated building information model

2.1 K-means Clustering Algorithm

K-means clustering algorithm is a classical clustering algorithm, and its main principle is to use distance to carry out the corresponding clustering division. When the two data are close, the distance between them is small, which means that the similarity between the two is high. K-means clustering algorithm is widely used in many important scientific fields because of its concise and fast characteristics and its high quality of data distribution and clustering. K-means clustering algorithm belongs to unsupervised clustering algorithm. This algorithm mainly classifies the existing data sets with multiple data sets through the internal rules of the algorithm, thus dividing the data sets into J categories. In this way, data sets within the same category can be highly similar. However, there are obvious differences in data similarity between different types of data sets. For example, if a sample data set A contains m data, the data set can be expressed as $A = \{a_1, a_2, \ldots, a_m\}$. First, in the original dataset A, J data objects are selected, and these data objects are used as the initial center of the category. Secondly, it is judged according to the similarity between each sample and J central categories. According to the judgment results, these data samples are allocated to the most appropriate category. Then, the average distance of each newly obtained class is recalculated and used as the cluster center. The process is repeated until no new cluster center is generated and the center point does not change, that is, the criterion function F is convergent. The target is determined according to the Euclidean distance between data categories. In the m-dimensional real number internal vector space, the Euclidean distance of two points is defined by the formula:

$$\mathrm{d}(\mathrm{a},\mathrm{b}) = \sqrt{(\mathrm{a_i} - \mathrm{b_i})^2} \tag{1}$$

Among them, $\mathrm{a_i}$ and $\mathrm{b_i}$ are the ith attribute values of a and b. The calculation formula of the criterion function definition is as follows:

$$\mathrm{F} = \sum_{\mathrm{i}=0}^{\mathrm{j}} \sum_{\mathrm{a}\in \mathrm{D_i}} |\mathrm{a} - \bar{\mathrm{a}}_\mathrm{i}|^2 \tag{2}$$

Among them, j is the total number of clusters and $\bar{\mathrm{a}}_\mathrm{i}$ is the center of $\mathrm{D_i}$. K-means clustering algorithm usually selects the criterion function as the sum of error squares criterion function. The calculation formula of this function is as follows:

$$Q_z = \sum_{i=1}^{j} \sum_{V\in D_i} ||V - N_i||^2 \tag{3}$$

Among them, V represents all individual sample data in cluster D_i. N_i is the arithmetic mean of all samples in cluster D_i. Q_z represents a mapping between the data object and the category center. The size of the Q_z values can feedback the sum of the squares of the error when m sample data are clustered into j clusters by the clustering algorithm. The numerical variation of Q_z can clearly reflect the error of data results. From the formula of this algorithm, it can be drawn the conclusion that to achieve the optimal data result of the sum of error squares, it is necessary to find the clustering that can make Q_z the minimum. This method is generally called the minimum difference partition.

2.2 Geographic Information System

To plan rail transit in a city, the basic model of the city must be obtained. Just like the urban electrified transportation network, to lay electricity in the city, it is necessary to make the corresponding network grid according to the overall situation of the city, so as to minimize the time and money spent [11]. The urban building data model needs the help of GIS. Geographic information system plays an irreplaceable role in many aspects, and its real-time sharing can access the information of the system anytime and anywhere.

The most important internal part of geographic information system is to collect corresponding urban geographic information from all walks of life to form a three-dimensional geographic information circle. Geographic information system mainly includes land use information, agricultural information, geological type information, etc. This kind of information can only be obtained with the assistance of different relevant departments. The system classifies, saves and manages this kind of data, and integrates information through data warehouse technology. As a very classic data integrated storage technology, data warehouse technology works better than traditional federated database. In terms of real-time efficiency, data integrity and technical procedure standardization, it is far superior to the traditional federated database technology. Data warehouse technology mainly includes four work contents, namely data extraction, data transformation, data cleaning and data loading. Through these four working links, data can be effectively imported into the geographic information system.

After the completion of geographic information collection, the data needs to be further processed, and the main steps of processing are two steps. The first step is to discretize the data. The main purpose of discretization processing is to improve the spatiotemporal efficiency of subsequent geographic information clustering, and to discretize the geographic information data with continuous attributes. The discrete formula is:

$$H_z = \left[\frac{(f_{z-1} + f_z)}{2}, f_z\right] \tag{4}$$

Among them, f is continuous attribute data and H is the initial interval grain set. The above formula is used to discretize the data until the continuous attribute discretization of geographic information is completed. After the data discretization is completed, the second step is to reduce the dimension of the data, which is called dimension reduction. Because of the diversity and complexity of geographic information types, the data dimension is very high and is not suitable for classification management. By reducing the dimension of data, the classification requirements of information system can be met, and the data can be classified quickly. The specific calculation formulas of dimension reduction are as follows:

$$A_{ik} = \frac{a_{ik} - \bar{a}_k}{b_i}, i = 1,2,\ldots,n; \ k = \mathrm{i} = 1,2,\ldots,\mathrm{q} \tag{5}$$

$$\bar{a}_k = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} a_{ik}}{\mathrm{n}} \tag{6}$$

$$V_k = \sqrt{\frac{\sum_{i=1}^{n}(a_{ik} - \bar{a}_k)^2}{n-1}} \tag{7}$$

Among them, q is the data dimension and a is the initial sample of data. n is the construction data sample matrix, a_{ik} is the original geographic information matrix. The solution of the characteristic formula can be obtained through the calculation formula, and its solution is expressed by S. By substituting the formula solution S into the following formula, the values of variance contribution rate and variance cumulative contribution rate Z and Z' can be obtained.

The variance contribution rate formula is as follows:

$$\mathrm{Z} = \frac{\mathrm{S_i}}{\sum_{\mathrm{g}=1}^{\mathrm{q}} \mathrm{S_g}} (\mathrm{i} = 1,2,\ldots,\mathrm{q}) \tag{8}$$

The formula of cumulative contribution rate of variance is as follows:

$$Z' = \frac{\sum_{g=1}^{i} S_g}{\sum_{g=1}^{q} S_g} (i = 1,2,\ldots,q) \quad (9)$$

Among them, S_i is the i-th eigenvalue and S_g is the g-th eigenvalue. q is the dimension and g is the data amount of the eigenvalue.

Through the calculation of the above clustering algorithm formula and geographic information system algorithm formula, all the requirements of the system can be met, and a complete three-dimensional GIS integrated building information model of urban rail transit line design system can be built.

3. Methodology and Validation: Functionality of the 3D GIS-Integrated Building Information System

3.1 Validation of Clustering Algorithm Performance

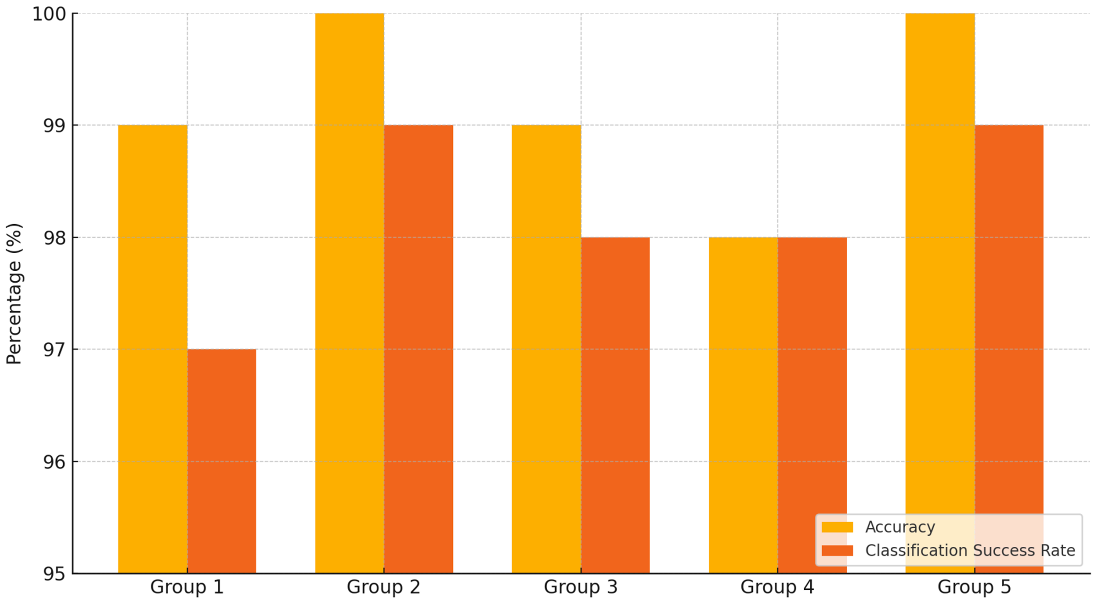

Figure 2. The accuracy and classification success rates of the clustering algorithm.

The clustering algorithm serves as the foundational element of the proposed system, playing a pivotal role in determining the viability of the system's operational model. To rigorously evaluate its performance, the algorithm was subjected to validation using two critical metrics: *Accuracy* Rate and *Classification Success* Rate. These metrics ensure that the clustering process meets the high standards required for practical implementation in complex urban rail transit planning scenarios. To assess the accuracy of the clustering algorithm, multiple sets of test data were prepared and analyzed. The results, depicted in the bar chart in **Figure 2**, demonstrate that the algorithm consistently achieved accuracy rates ranging between 98% and 100%, with all values exceeding the pre-defined benchmark of 95%. This level of accuracy highlights the robustness of the algorithm in handling the intricate data structures required for urban transit design. The observed variations, though minimal, are attributable to the inherent complexity of the input data. Nonetheless, the results underscore that the clustering algorithm reliably performs within acceptable error margins.

Further analysis was conducted to evaluate the algorithm's classification success rate, which measures its ability to correctly categorize data points into distinct clusters. As shown in the same chart, the success rates varied between 95% and 100%, aligning closely with the accuracy results. Notably, while there was slightly greater variability in success rates compared to accuracy, this can be attributed to the presence of ambiguous data points, which naturally challenge the algorithm's decision-making process. Despite these challenges, the classification success rates consistently met the experimental threshold, reinforcing the algorithm's efficacy in real-world applications. The combined results of the accuracy and classification success rate tests confirm the clustering algorithm's capability to operate without significant anomalies. These findings are indicative of the algorithm’s reliability and its ability to manage complex, large-scale datasets efficiently. The algorithm's performance forms a strong foundation for the subsequent stages of the system's design and analysis, ensuring that the generated urban rail transit models are both accurate and practical for implementation.

3.2 Evaluation of Geographic Information System Functionality

The Geographic Information System (GIS) serves as the foundational component of the proposed system, enabling the identification of clustered data and the virtual modeling of urban building information. To assess its functionality, two primary performance metrics were examined: the success rate of data recognition and the success rate of urban building information modeling. These metrics ensure that GIS operates efficiently within the integrated system. The established benchmark for these tests was a performance threshold of 90%, meaning that any system achieving a rate above this threshold could be deemed operationally effective.

For the experimental analysis, multiple groups of randomly selected test data were evaluated to verify the GIS functionality. **Figure 3** presents the comparative results of GIS data recognition rates and GIS modeling success rates across the test groups. The results indicate that the GIS data recognition rates consistently exceeded 95%, with the highest rate observed at 100%. The lowest rate, recorded at 96%, suggests that occasional minor inconsistencies may arise due to data interference. Despite this, the overall recognition capability of GIS remains robust, effectively processing and classifying urban geographic data. Similarly, the GIS modeling success rates demonstrated exceptional stability and precision, with most test groups achieving a success rate of 100%. Even the lowest recorded rate, at 99%, aligns with the operational expectations of the system, highlighting the reliability of the GIS component in generating accurate virtual models of urban structures. Overall, these findings confirm that the GIS module functions seamlessly, fulfilling its intended role within the integrated system. The high-performance metrics observed across both data recognition and modeling tasks validate the effectiveness of GIS in supporting the design of urban rail transit systems. This evaluation underscores the system's readiness for practical implementation, with no significant anomalies detected in the GIS functionality.

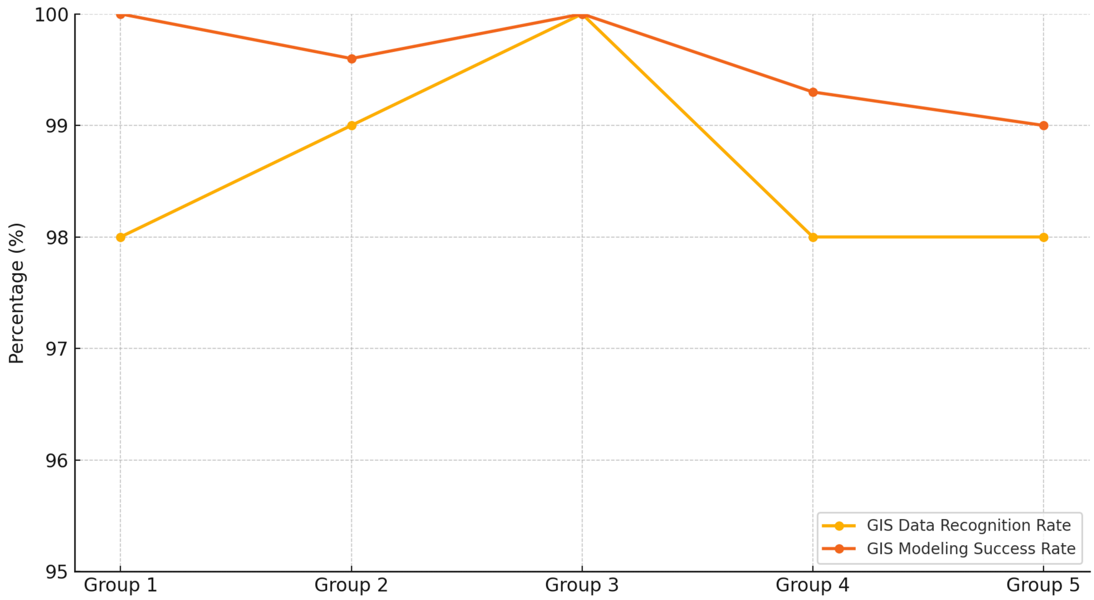

Figure 3. GIS data recognition and modeling success rates.

4. Data Comparison between Traditional Scheme and System Scheme

Through the experimental test of urban rail transit line design system based on 3D GIS integrated building information model, it is finally confirmed that the system can work normally. However, the original intention of this system is to solve the problem of urban vehicles more effectively. To judge whether the system can solve the problem more effectively, a reference is needed to compare the performance indicators of the system, so as to achieve the purpose of solving the problem effectively. Therefore, this paper chooses to compare the traffic scheme designed by the urban rail transit line design system based on 3D GIS integrated building information model (hereinafter referred to as the system scheme) with the traffic scheme designed by traditional methods (hereinafter referred to as the traditional scheme). Through data analysis, the advantages and disadvantages of the system scheme in various data are intuitively understood. The main data for this data comparison include:

scheme integrity, scheme scientificity, scheme design time, scheme design cost, scheme satisfaction and scheme use intention.

4.1 Comparison of Scheme Integrity and Scientific Data

In the planning and design of modern cities, more and more urban planners begin to attach importance to and use 5G technology to carry out digital urban planning. In rail transit, the proportion of 5G technology is also increasing [12-13]. Therefore, 5G technology was also integrated into this system. Modern machinery and equipment were used to carry out scientific planning for urban rail transit, making the rail transit planning more complete and scientific. In order to analyze the scientificity and completeness of the system scheme, this paper selected a city to plan urban rail transit through the form of system scheme and traditional scheme. The comparative analysis of urban rail transit planning integrity and scientific data is shown in **Figure 4** (**Figure 4a** shows the comparative analysis of urban rail transit planning integrity data, and **Figure 4b** shows the comparative analysis of urban rail transit planning scientific data).

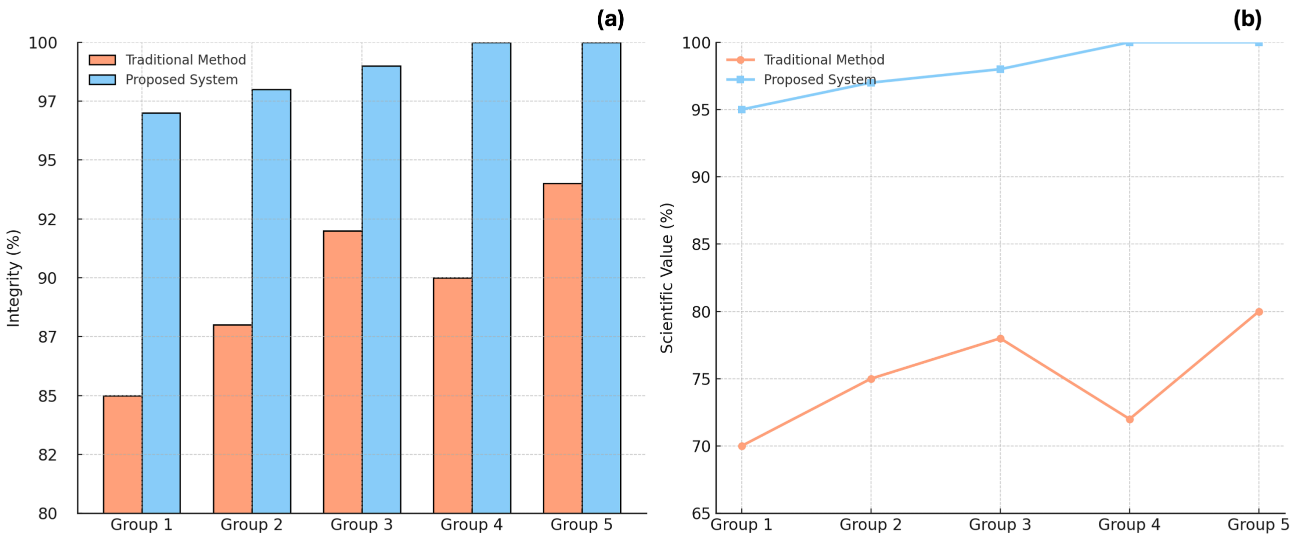

Figure 4. Comparative analysis of urban rail transit planning integrity and scientific data (a) the urban rail transit planning integrity data and (b) the comparative analysis of urban rail transit planning scientific data.

It can be clearly seen from the data in the comparative analysis of urban rail transit planning integrity and scientific data in **Figure 4** that the system scheme was far higher than the design scheme proposed by traditional methods, whether in terms of the integrity or scientific nature of urban rail transit planning. In the aspect of urban rail transit planning integrity, the minimum integrity value of the traditional scheme was 85%, while the maximum integrity value was only 94%. The integrity difference was 9%. The integrity of the design scheme proposed by the design system in this paper was 97% at the lowest, 100% at the highest, and only 3% at the difference. The maximum integrity of 100% plus the integrity difference of only 3% can fully demonstrate the superiority and stability of the system in terms of scheme integrity.

In the comparative analysis of scientific data of urban rail transit planning, the highest scientific value of the traditional scheme was 80%, and the lowest scientific value was 70%. The scientific difference was 10%. The highest scientific value of the system scheme was 100%, and the lowest value was 95%. The scientific difference was 5%. In terms of the scientific nature of urban rail transit planning, the traditional plan is mostly manual planning, which can consider limited aspects and problems, and it is difficult to carry out comprehensive planning analysis. Therefore, there are inevitably errors in the scientific nature of planning. The design scheme proposed by the system is to collect all existing problems as data reference, which can avoid many problems that have existed before. However, whether the design is scientific or not is ultimately determined by people. Therefore, in terms of new problems, it is difficult for the system scheme to be 100% scientific without data reference.

4.2 Comparison of Scheme Design Time and Cost Data

In the design of urban rail transit, there are many specific factors that affect the scheme design, such as design time, planning area, design cost, window maintenance, etc. These factors are all regarded as an important reference index of urban rail transit [14]. In the design of urban rail transit, it is necessary to consider not only the railway itself, but also the pollution of rail transit [15]. In this regard, the main focus is on the time and cost of design. As a public welfare project, whether the construction of urban rail transit can be completed quickly and how much the financial cost are all issues that the relevant departments attach great importance to. Therefore, in terms of time and cost of scheme design, the data were compared with those of traditional schemes. The comparative analysis of time and cost data of scheme design is shown in **Figure 5** (**Figure 5a** shows the comparative analysis of time data of scheme design, and **Figure 5b** shows the comparative analysis of cost data of scheme design).

According to the data in the comparative analysis of scheme design time and cost data in **Figure 5** in terms of design time, the shortest time value of traditional scheme design was 7 days, while the longest design time was 10 days. The time difference was 3 days. The minimum design time of the system scheme was 1 day, the maximum time value was 2 days, and the difference was 1 day. Therefore, in the aspect of design time, the traditional scheme can’t beat the system scheme. In terms of the actual cost budget of the scheme, the cost budget of the traditional scheme was at least 120,000

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RMB, and the maximum budget was 200,000 RMB. The budget cost difference was 80,000 RMB. Such huge fluctuation difference is mainly due to the manual calculation method used in the traditional scheme. Therefore, it is impossible to accurately grasp the details and expenses in all aspects, and this kind of situation of excessive budget expenditure appears. The system scheme gives an accurate value for each cost. Therefore, the design budget cost of the system scheme is very stable. The maximum budget cost was 50,000 RMB and the minimum budget cost was 20,000 RMB. The cost difference was 30,000 RMB. Therefore, in terms of the same sample design requirements, the time and cost of the traditional scheme is higher than that of the system scheme, whether in terms of design time or cost budget.

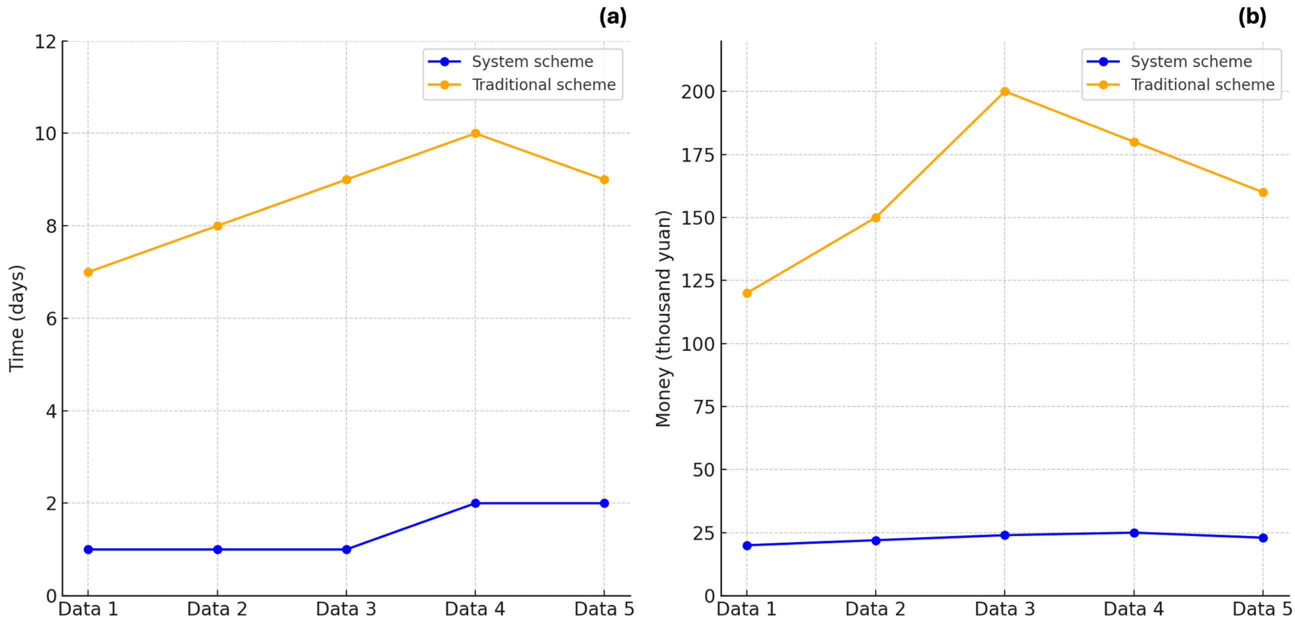

Figure 5. Comparative analysis of scheme design time and cost data (a) the comparative analysis of time data of scheme design and (b) the comparative analysis of cost data of scheme design.

4.3 Survey of Scheme Design Satisfaction and Scheme Mode Selection Data

Through the comparison and analysis of the above four data, it can be basically judged that the system scheme is superior to the traditional scheme in all aspects. However, the final judge of any scheme needs to be judged by people. Therefore, for the two methods, this paper selected 100 government personnel for survey and interview, and divided the data sample of these 100 respondents into 10 groups, with 10 people in each group. The following 100 respondents' program satisfaction and willingness to use data (5 groups respectively) were obtained. The comparative analysis chart is shown in **Figure 6** (**Figure 6a** shows the comparative analysis of scheme satisfaction data, and

Figure 6b shows the comparative analysis of scheme use intention data).

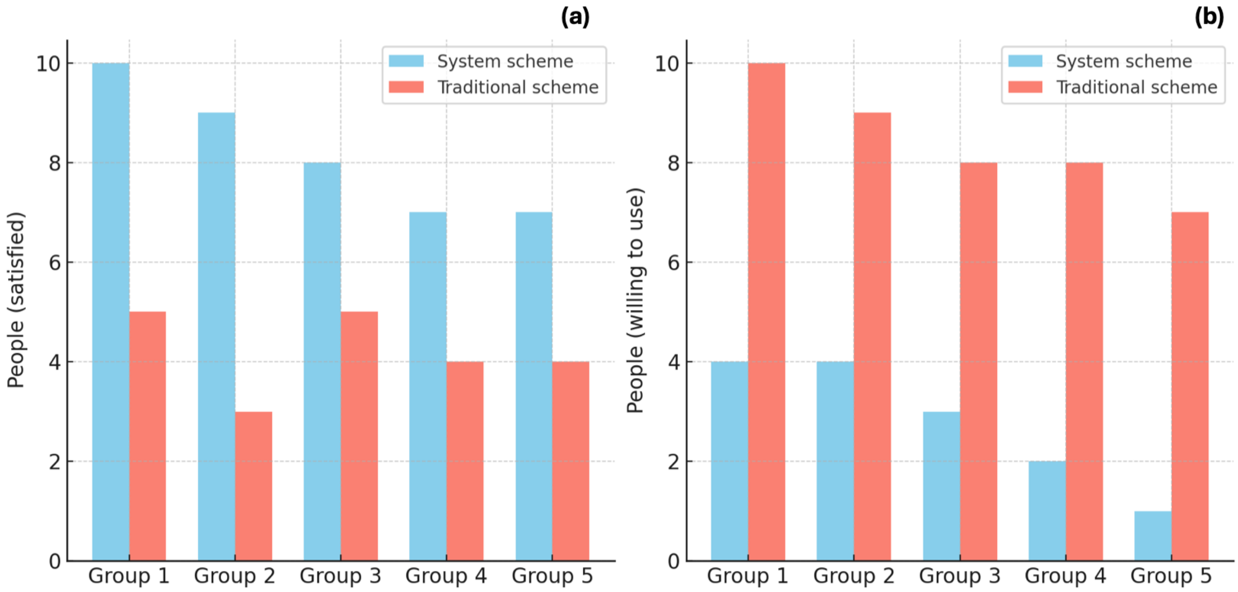

Figure 6. Comparative analysis of scheme satisfaction and willingness to use data.

From the survey data in the comparative analysis of case satisfaction and use intention data in **Figure 6**, it can be clearly seen that the group with the highest use satisfaction of the traditional scheme was the third group, and the number of satisfied people was 5. The group with the lowest satisfaction was the second group, with only 3 satisfied people and 40% overall satisfaction. The group with the highest satisfaction with the use of the system scheme was the first group, with 10 people satisfied. The group with the lowest satisfaction was the fifth group, and the number of satisfied people also reached 7, with a comprehensive satisfaction rate of 86%. In terms of program satisfaction, the difference between traditional and system program satisfaction was 46%, which is enough to explain many problems.

However, there is a strange phenomenon in the survey of willingness to continue using the program. In the survey of the willingness to continue using the program, the group with the highest willingness to continue using the traditional program was the first group, with 10 people. The group with the lowest willingness to continue using was the fifth group, with 7 people, and the comprehensive willingness to continue using rate was 86%. The group with the highest number of people willing to continue using the system scheme was the second group, with 4 people. The lowest group was the fifth group, with 1 person, and the comprehensive willingness to continue using was only 24%. In terms of the rate of willingness to continue using, the system scheme was completely defeated by the traditional scheme. In order to understand the reasons for this situation, the survey team asked the interviewees in detail.

Most of the interviewees said that the traditional labor plan had a large budget, which was more conducive to the implementation of the plan.

5. Current Limitations and Future Directions

5.1 Current Limitations

Despite the demonstrated advantages of the 3D GIS-integrated BIM system for urban rail transit design, several limitations remain evident and require attention. These limitations span technical, cultural, and operational dimensions, each posing challenges to the system’s implementation and broader acceptance. From a technical standpoint, the reliance on the K-means clustering algorithm introduces inherent constraints. While effective for segmenting data, the algorithm struggles with highly dynamic or non-linear datasets, which are common in urban environments characterized by rapid and unpredictable changes in traffic patterns. This rigidity limits the system’s ability to adapt to atypical scenarios or emerging urban conditions, potentially undermining its predictive accuracy in complex real-world settings. Additionally, the integration of GIS and BIM technologies, while innovative, necessitates significant computational resources. The system's current reliance on advanced hardware may not be feasible in all contexts, particularly in resource-constrained urban areas, where the cost of infrastructure could deter adoption. Another technical challenge lies in the variability of GIS data quality. The system assumes consistent and accurate input data, yet urban data sources often differ significantly in terms of completeness and reliability. Such inconsistencies can lead to errors in the design process and diminish the system’s utility.

Cultural and user-related challenges further complicate the adoption of this system. The low willingness to adopt the proposed solution, as reflected in survey results, points to deeply ingrained reliance on traditional methods of urban planning. Stakeholders, particularly municipal planners, often demonstrate a preference for established practices due to their familiarity and the perceived reliability of conventional approaches. The novel nature of the proposed system may evoke skepticism, compounded by the perceived complexity of its interface and the significant learning curve it presents. Planners and decision-makers may view the system as overly technical or inaccessible, creating resistance to its integration into standard workflows.

Operationally, the scope of the system presents additional constraints. While the focus on rail transit design offers substantial benefits in addressing urban congestion, this approach does not encompass the broader spectrum of urban mobility needs. Multi-modal transportation systems, including bus networks, pedestrian pathways, and cycling infrastructure, are critical components of urban planning, yet they remain outside the system’s current purview. Moreover, the financial implications of implementation require consideration. Although the system reduces costs during the design phase, deploying and maintaining the required infrastructure, including sensors and data management units, could escalate expenses in the long term.

5.2 Future Directions

To overcome these limitations and enhance the utility of the proposed system, several avenues for future development emerge, emphasizing the need for technical refinement, broader integration, and greater stakeholder engagement. Addressing technical limitations necessitates advancements in algorithmic capabilities. The incorporation of more sophisticated models, such as neural networks or hybrid systems that combine K-means clustering with machine learning techniques, would allow the system to handle complex and dynamic urban datasets more effectively. These enhancements could improve the system's adaptability and precision in rapidly evolving urban contexts. Additionally, enabling real-time data processing would position the system as a responsive tool capable of reflecting ongoing urban changes, such as road closures or surges in traffic demand, thus ensuring its continued relevance and accuracy.

Expanding the system’s scope is equally critical. Incorporating multi-modal transportation planning capabilities would enable the design of integrated urban mobility solutions, addressing the diverse needs of modern cities. This expansion could include modeling for bus routes, pedestrian zones, and cycling networks, creating a more comprehensive and versatile planning tool. Integration with emerging technologies, such as autonomous vehicles and electric transit systems, would further broaden the system's applicability and align it with contemporary trends in urban mobility innovation.

The cultural and operational barriers identified in this study underscore the importance of fostering user acceptance through targeted engagement and support. Pilot projects and collaborative workshops with urban planners and policymakers could facilitate trust-building and provide valuable feedback for refining the system. These initiatives would also help demonstrate the system’s practical benefits, potentially shifting stakeholder perceptions and reducing resistance. Simplifying the system’s interface and offering tailored training resources could address concerns about accessibility, making the tool more user-friendly and adaptable to diverse planning contexts.

Finally, future research should explore the long-term policy and sustainability implications of adopting the system. Demonstrating quantifiable benefits, such as reductions in greenhouse gas emissions and improved land use efficiency, would bolster the system's appeal to policymakers and urban stakeholders. Collaborations with governmental agencies and regulatory bodies could support the development of frameworks and incentives to facilitate its deployment. Strengthening data quality and standardization through robust protocols and partnerships would further enhance the system's reliability, addressing a critical technical limitation and ensuring consistent performance.

6. Conclusions

The development and implementation of this paper's design have considered both scientific rigor and the human environmental context integral to urban planning. Following an extensive review of existing literature on urban transportation systems, the study adopts an innovative approach by designing an urban rail transit line system grounded in a 3D GIS-integrated Building Information Modeling (BIM) framework. This system was rigorously evaluated against traditional design methodologies to assess its performance and applicability. Comparative analysis of the experimental data indicates that the proposed system demonstrates superior performance across most metrics. Notably, it excels in parameters such as design accuracy, efficiency, cost-effectiveness, and operational stability. However, a significant divergence arises in the metric of user willingness to adopt the system, which remains lower compared to traditional methods. This reluctance is not attributed to deficiencies in the system's technical design or functionality but rather reflects external factors, such as cultural perceptions and user familiarity with traditional approaches. Despite this limitation, the results underscore the system's robustness and potential for practical application.

The urban rail transit line design system leveraging 3D GIS and BIM technology addresses critical gaps in existing urban transport planning by providing a more systematic, data-driven, and adaptable solution. Consequently, it can be responsibly concluded that this system represents a scientifically sound and technically feasible contribution to urban rail transit design, with the potential to significantly enhance the efficiency and sustainability of urban transportation networks when appropriately implemented and contextualized.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing Interests

All authors declare no Competing Financial or Non-Financial Interests.

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Author Contributions:

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