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CASE STUDY: OPTIMIZATION OF UNDERGROUND CAR PARK DESIGN AND SAFETY ASSESSMENT

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ABSTRACT

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The development of underground space is a very complicated process, and the traditional 2D-based approach in engineering is not enough to solve the problems encountered. The 3D visualization brought by BIM technology greatly improves the accuracy of design and construction. This paper's case is the underground parking lot development project of Shanghai International Shipping Service Center. The underground parking lot design and optimization is based on the Building Information Modeling (BIM)+ traffic simulation technology. And according to the actual condition of the parking lot, we established a safety evaluation index system, and constructed a micro-simulation road network through VISSIM, so that we can determine potential safety conflict points on each floor and make recommendations. Finally, based on fuzzy evaluation theory and analytic hierarchy process, we evaluated the safety level of the underground parking lot. The safety evaluation result shows that the junction of the passageway from the B2 to B1 is the main point of security conflict, and it is necessary to set up corresponding warning signs and guidance measures at these locations. The BIM + traffic simulation technology adopted in this paper is a new model, and this research has reference value for the development of urban underground parking systems.

Contribution/Originality: The paper provide a new mode of BIM technology used: BIM + traffic simulation technology, and this research has reference value for the development of urban underground parking systems.

1. INTRODUCTION

The world is in the process of rapid urbanization. The rapidly expanding cities have higher demand for infrastructure. Effective and integrated use of underground space is of great significance for improving the living standards of cities, especially for densely populated cities [1]. Underground parking lot can effectively use land without reducing the area of green space. It is a very effective method to alleviate urban traffic congestion and solve the problem of difficult parking. In the design and development of underground parking lots, developers focus on

the issues of construction area and cost control. A high-economic design scheme of underground parking garage is very essential to control the construction cost of underground parking garages.

The case in this paper is selected from the development project of Shanghai International Shipping Service Center (SISSC). The design and optimization of the underground parking lot is based on BIM + traffic simulation technology. And the final scheme was evaluated for security level, by establishing a fuzzy evaluation model.

The research can provide a reference for the planning and design of urban underground parking systems.

2. LITERATURE REVIEW

The development of underground space is a large-scale and time-consuming project, which requires complicated technology. At the same time, there are a lot of random factors at each stage. These characteristics make it difficult to achieve project goals. The traditional methods mainly based on 2D in engineering are insufficient to solve the problems encountered. The 3D visualization brought by BIM technology has greatly improved the accuracy of design and construction [2]. Not only that, BIM technology can help identify and evaluate risk factors in the project and provide effective support for the entire life cycle of the project. The BIM industry working group [3] said that the British government believes that the use of BIM technology throughout the project life cycle can bring high efficiency and high returns. Through investigation and analysis of 204 construction projects, Hwang, et al. [4] found that projects implementing BIM often have lower rework rates. Ustinovičius, et al. [5] concluded in «Challenges of BIM technology application in project planning» that the proper use of BIM technology design can help users avoid mistakes and reduce the loss of financial resources.

The implementation of BIM technology may affect all processes of the project, Howard and Björk [6] emphasized that it should be comprehensively managed rather than treated in isolation as a software tool. The proposal of BIM + theory extends BIM from the technical level to the fields of production organization and operation management. In the article «From BIM to Geo-analysis: View Coverage and Shadow Analysis by BIM / GIS Integration», Rafiee, et al. [7] stated that the combination of BIM and GIS can form a more comprehensive system to help urban planners, architects and others carry out analysis for different purposes. The project in this paper used BIM + traffic simulation technology.

Computer simulation technology has been widely used in the field of traffic engineering since the 1970s. In the 1990s, most traffic system simulation applications are based on vehicle-to-vehicle interaction patterns and are microscopic in nature [8]. VISSIM, officially released by PTV Transworld AG in 1993, is a micro-simulation model based on time intervals and driving behavior. It is usually used for traffic modeling of urban transportation and public transportation operations. VISSIM can reproduce the traffic flow under different traffic conditions in the real world [9]. At the same time, it allows users to adjust the model parameters to reflect the traffic conditions under specific actual conditions [10].

3. DESIGN AND OPTIMIZATION OF PARKING GARAGE

3.1. Design Ideas

The design plan of the parking garage should comprehensively consider the specific building space of the parking garage and the actual needs, and scientifically optimize the layout of the parking spaces and parking passages.

(1) Establish the base map according to the initial construction plan of the parking garage.

Mark the relevant information in the base map, including the entrance and exit positions of the parking garage, the available parking space, the location, shape and size of obstacles. Obstacles include building pillars, equipment land, and house land where all parking spaces cannot be constructed.

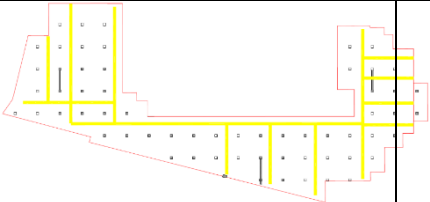
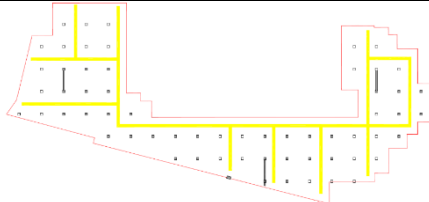

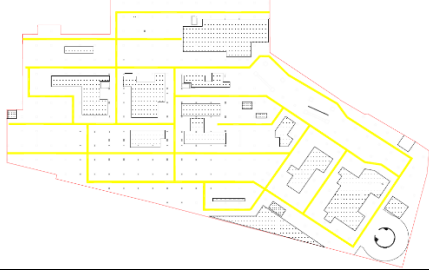
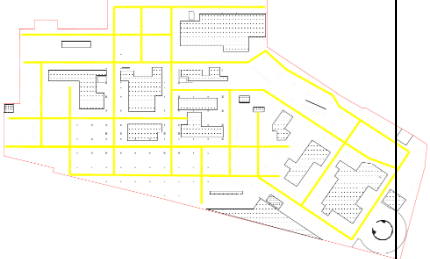
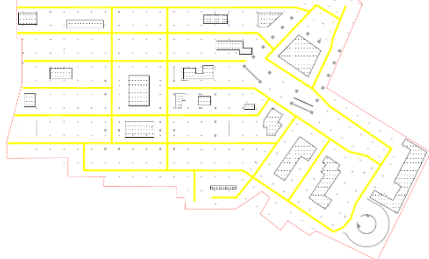
(2) According to the obstacles and the location of the garage entrance and exit, design the main road distribution plan inside the garage to get the road network distribution map.

- (3) Mark the boundary of the main road in the CAD base map according to the distribution of the road network, and import it into the BIM system, and get the design plan automatically.
- (4) Use traffic simulation software to conduct safety assessment of internal channels and nodes, readjust and design the parking garage plan, and finally obtain a scientific and reasonable parking garage floor plan.

3.2. Design Scheme

The two initial design schemes are shown in Table 1.

Table-1. Initial design scheme.

	Scheme 1	Scheme 2
B1		
B2		
B3		

Import the base map into the BIM system to get the number of parking spaces for the two options.

Table-2. Number of parking spaces.

	Basement 1	Basement 2	Basement 3
Scheme 1	115	480	660
Scheme 2	130	515	680

In the Table 2, it can be seen that the scheme 2 has more parking spaces and higher space utilization, and the location of parking spaces and the direction of parking passages are more reasonable.

Mark the entrance and exit positions of the parking garage, available parking space, obstacles and other related information in the selected design diagram.

The design and optimization plan of the three floors of the parking garage are shown in Table 3. Red is the garage boundary, purple is the parking space, green is the road boundary, black is the obstacle boundary, and pink is the barrier-free parking space boundary.

Table-3. The design and optimization plan.

<p>Basement 1</p>	
<p>Basement 2</p>	
<p>Basement 3</p>	

4. SAFETY EVALUATION ANALYSIS OF PARKING LOT

4.1. Safety Evaluation Index

Research on safety evaluation indicators can be roughly divided into three categories: risk indicators, accident indicators, and hidden danger indicators. Ex-ante risk assessment mainly uses hidden danger indicators for evaluation.

The study of parking lot traffic safety is a special systematic project. In the process of parking, the probability of a traffic safety accident is low, and the damage and impact of the accident are not very serious. However, from the perspective of system engineering, there are still many conflict points, and these hidden danger indicators for parking safety.

Divide the parking lot into exit and entrance sections and internal sections for safety evaluation.

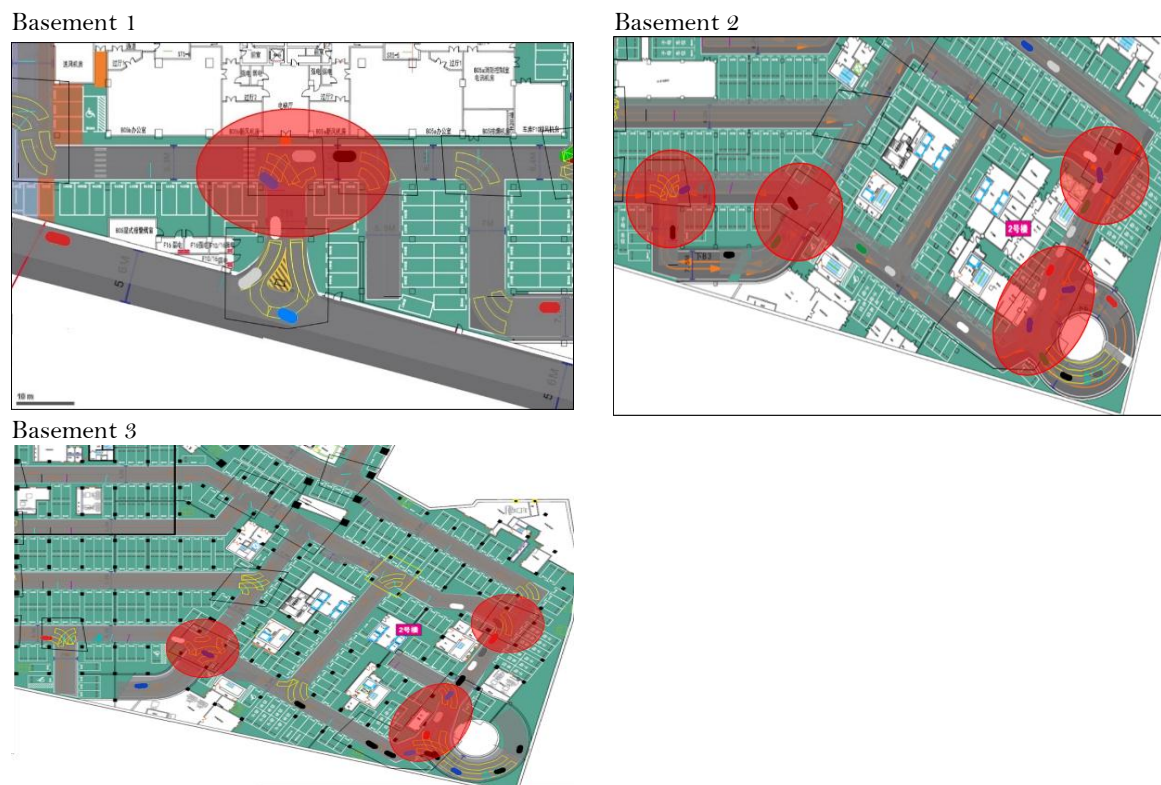
The evaluation of the entrance and exit sections is mainly based on road network conditions and interference conditions, including the service level of adjacent road sections, obstacle rate of traffic interference, lane length, line-of-sight safety, and service level.

The evaluation of internal sections is mainly based on the situation of conflict points and key passages, including the type of intersection, traffic flow, turning radius, the slope and width of the passage, the number of conflict points, and the flat curve rate of the lane.

4.2. Microscopic Simulation Model of Parking Lot

Use VISSIM micro-simulation software to build a simulation road network and determine potential security conflict points (red circled in Table 4) at each layer. The conflict point has the following characteristics: near the entrance and exit, the traffic volume is relatively large, and the intersection has multidirectional traffic flow. It is recommended to set up safety warning signs and arrange facilitators for control and mediation in the actual operation process.

Table-4. Simulation road network of underground parking lot.



4.3. Fuzzy Comprehensive Evaluation Model

In complex large systems, factors at different levels and different aspects often need to be considered. For such cases, it is usually necessary to classify the set of judgment factors according to attributes, then make a comprehensive evaluation according to the category classification, and finally perform a high-level comprehensive evaluation between the categories on the results of various types of assessment. Fuzzy comprehensive evaluation can be divided into first-level fuzzy evaluation model and multi-level fuzzy evaluation model.

The fuzzy comprehensive evaluation of this paper is multi-level.

Follow the steps below to build a multi-level fuzzy comprehensive evaluation model.

(1) According to an attribute, the evaluation factor set U is divided into m subsets, then make it satisfied :

$$\begin{cases} \sum_{i=1}^m U_i = U \\ U_i \cap U_j = \Phi (i \neq j) \end{cases}$$

then get the second-level evaluation factor set:

$$U = \{U_1, U_2, \dots, U_m\}$$

$U_i = \{U_{ik}\} (i=1,2,\dots, m; k=1,2,\dots, n_k)$ means that subset U_i contains n_k evaluation factors.

(2) For the n_k factors in each subset of U_i , assess them according to the single-level fuzzy comprehensive evaluation model. If all factors weight distribution in U_i is A_i , and the evaluation decision matrix is R_i , then get the comprehensive evaluation results of the i subset U_i :

$$B_i = A_i \times R_i = [b_{i1}, b_{i2}, \dots, b_{in}]$$

(4) Assess the m subset $U_i (i=1,2, \dots, m)$ in U comprehensively and get the decision matrix:

$$R = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_m \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \dots & b_{mn} \end{bmatrix}$$

If the weight distribution of each factor subset in U is A, then get the comprehensive evaluation results:

$$B^* = A \times R$$

In the formula (5), B^* is the comprehensive evaluation result of U, and also the comprehensive evaluation result of all evaluation factors in U.

If there are still many factors in U, divide it again then can get multi-level evaluation model. The multi-level fuzzy comprehensive evaluation model can not only show the factors' different levels, but also avoid the difficulty of weight distribution due to too many factors.

4.4. Safety Evaluation of Basement 1

The B1 area was divided and screened, and 7 intersections and 3 main passages were selected for safety assessment.

4.4.1. Calculation of Weights

According to the analytic hierarchy process (AHP), and the expert's scoring method, compare the importance of the same-layer factor index to the upper-layer factor, then can get pairwise comparison $n \times n$ order judgment

matrix A. Let $A = [a_{ij}]_{n \times n}$, and $a_{ij} = \frac{w_i}{w_j}, a_{ij} > 0, \sum a_{ij} = 1, a_{ij} = \frac{1}{a_{ji}}$. The matrix has the

unique nonzero maximum eigenvalue $\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(AW)_i}{w_i}$, and $\lambda_{\max} = n$.

The five indicators of the intersection evaluation were marked as N11, N12, N13, N14, N15, respectively.

Compare them to each other, then can get the membership degree W_i as shown in Table 5 :

(The membership degree W_i is the qualitative evaluation index to each previous layer, which is the relative weights of each layer of factors.)

Table-5. Weight calculation of various factors at the intersection.

N	N1	N2	N3	N4	N5	W_i
N1	1	0.5	0.5	0.33	1	0.11
N2	2	1	0.67	0.5	1	0.17
N3	2	1.5	1	1	2	0.27
N4	3	2	1	1	2	0.31
N5	1	1	0.5	0.5	1	0.14

Calculate the maximum eigenvalue of each comparison matrix and the corresponding normalized eigenvector,

get $\lambda_{max} = 5.05$. And consistency index $(CI) = \frac{\lambda - n}{n - 1} = 0.012$, consistency ratio

$(CR) = \frac{CI}{RI} = 0.010$. $CR < 0.1$, so this weight matrix is acceptable.

Similarly, the five indicators of passageway evaluation were marked as L11, L12, L13, L14, L15, respectively. The relative weights are shown in Table 6:

Table-6. Weight calculation of each factor in the passageway.

L	L1	L2	L3	L4	L5	W_i
L1	1.00	1.50	0.67	0.50	1.00	0.16
L2	0.67	1.00	0.50	0.50	1.00	0.13
L3	1.50	2.00	1.00	1.50	2.00	0.29
L4	2.00	2.00	0.67	1.00	1.50	0.25
L5	1.00	1.00	0.50	0.67	1.00	0.15

Consistency ratio $(CR) = \frac{CI}{RI} = 0.011$, $CR < 0.1$, so this weight matrix is acceptable.

The five indicators of entrance and exit evaluation were marked as E11, E12, E13, E14, E15, respectively. The relative weights are shown in Table 7:

Table-7. Weight calculation of each factor in the entrance and exit.

E	E1	E2	E3	E4	E5	W_i
E1	1.00	0.50	0.67	0.50	0.33	0.10
E2	2.00	1.00	2.00	1.50	1.00	0.27
E3	1.50	0.50	1.00	0.67	0.50	0.14
E4	2.00	0.67	1.50	1.00	0.50	0.19
E5	3.00	1.00	2.00	2.00	1.00	0.31

Consistency ratio $(CR) = \frac{CI}{RI} = 0.008$, $CR < 0.1$, so this weight matrix is acceptable.

4.4.2. Calculation of System Evaluation Values

The following data Table 8 was obtained through VISSIM simulation, including intersection traffic, left-turn vehicle proportion, related car seats, and intersection service level.

Table-8. VISSIM simulation data.

Intersection	Total flow (veh)	Left turn	Straight on	Right turn	Ratio of Left turn(%)	Delay time(s)
HN1	25	10	15	0	40%	0.3
HN2	30	0	5	25	0%	0.4
HN3	44	0	30	14	0%	1.1
JN1	14	0	14	0	0%	0.9
JN2	34	12	8	14	35%	1.6
JN3	306	272	34	0	89%	11.1
JN4	315	9	306	0	3%	5.4
JN5	374	313	0	61	84%	4.4
Entry&Exit	373	--	--	--	--	1.7

Then normalize the raw data and use it for data analysis. The min-max normalization method used in this project is linear transformation of raw data. Set minA as the minimum values of intersection flow and maxA as maximum values. Map an original value x of A to the value x' in the interval [45,95] through min-max normalization, the formula is:

$$x' = \frac{x - \min A}{\max A - \min A} * 50 + 45$$

Score the Intersection turning radius according to the degree of minimum turning radius. If the two values are equal, scores 75. If turning radius is larger, scores 85.

For the different intersection road type, the T-shaped intersection score is 50, and the cruciform intersection score is 30.

The value range of the safety indicators is from 0 to 100, a larger value means a higher safety degree. As shown in Table 9 to Table 11.

Table-9. Intersection evaluation value.

Intersection	Type	Flow	Turning radius (Score)	Left-turn vehicle ratio	Delay
HN1	50	93.5	72.5	72.5	95.0
HN2	50	92.8	95.0	95.0	94.5
HN3	50	90.8	95.0	95.0	91.3
JN1	50	95.0	95.0	95.0	92.2
JN2	30	92.2	75.1	75.1	89.0
JN3	50	54.4	45.0	45.0	45.0
JN4	50	53.2	93.4	93.4	71.4
JN5	50	45.0	47.9	47.9	76.0

Table-10. Passageway evaluation value.

Channel	Slope	Width	Intersection	Channel traffic flow	Curvature
L1	100	95.0	60	45.0	100
L2	100	57.5	80	95.0	100
L3	100	45.0	70	92.7	100

Table-11. Evaluation value of entrance and exit.

Passageway	E1
Service level of adjacent roads	62
Obstacle rate of traffic interference	100
Lane length	50
Exit services level	80
Horizon security	60

4.4.3. Analysis of Evaluation Results

According to model $B^* = A \times R$, the total safety evaluation score of the system is calculated in Table 12:

Table-12. Evaluation result score.

Intersection	R	Color
HN1	80.07	
HN2	88.11	
HN3	87.32	
JN1	85.50	
JN2	74.88	
JN3	56.53	
JN4	74.88	
JN5	60.19	
Passageway		
L1	71.61	
L2	85.82	
L3	80.31	
Entry & Exit		
E1	70.57	

This project uses 4 levels to evaluate the security status of the system, as shown in Table 13.

Table-13. Security scale of evaluation results.

Composite score	<60	60-75	75-85	85-100
Evaluation results	Bad	Not bad	Good	Great
Color	Red	Orange	Yellow	Green

Identify on the map and shown in Figure 1.

5. CONCLUSION

This case is selected from the development project of Shanghai International Shipping Service Center (SISSC) underground parking lot. The project uses BIM and traffic simulation technology to design and optimize the parking space setting and parking aisle. The final design plan is Table 3. The safety level of the parking lot was evaluated by constructing a micro-simulation road network of the parking lot and establishing a fuzzy comprehensive evaluation model.

The simulation focuses on the peak hours of off-hours. It examines the parking lot operation in the case of concentrated high-density traffic in one direction, and quantitatively evaluates the safety evaluation levels at the entrances and intersections of each floor.

The safety evaluation result shows that the junction of the passageway from the B2 to B1 is the main point of security conflict. The reason is that the passage on the ground floor not only serves the parking spaces on this floor, but also bears the ingress and egress of vehicles on the rest of the floors. In addition, there is a certain security risk

at the intersection of each floor near the entrance and exit. Corresponding warning signs and guidance measures should be set at these locations.

This paper provide a new mode of BIM technology used: BIM + traffic simulation technology, and this research has reference value for the development of urban underground parking systems.

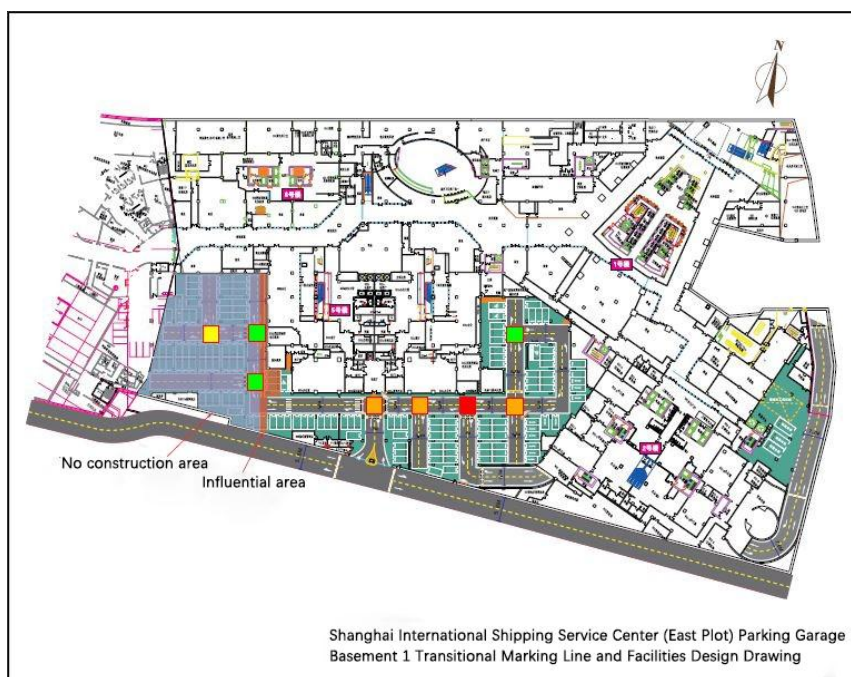


Figure-1. Evaluation results.

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