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BIM-based safety design for emergency evacuation of metro stations

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Abstract

Metro stations are the hubs of urban rail transit, and large numbers of people usually gather inside them. Various types of emergency can lead to a need for evacuation. However, there are few studies on proactively reducing emergency evacuation risks through the design for safety (DFS) concept, and these risks pose serious threats to the operational safety of metro stations. Therefore, in this research, fragmented DFS pre-control measures for mitigating emergency evacuation risks were comprehensively identified and classified, and indicators for evaluating the evacuation design effect on reducing emergency evacuation risks in the operation phase were improved. Moreover, through the combination of the DFS application method and BIM platform, intelligent safety design tools were provided for metro station designers so that they may apply the DFS concept to emergency evacuation risk mitigation in real cases.

Keywords: Metro station, Emergency evacuation, Design for safety (DFS), Queuing theory, Building information modeling (BIM)

1 Introduction

In recent years, China has been experiencing a rapid increase in urbanization. Metros, as an efficient and convenient transportation mode, have effectively relieved the tremendous pressure of urban traffic. By the end of 2018, 35 cities in mainland China had completed the construction of 5766.6 kilometers of urban rail transit lines. The average daily passenger traffic of urban rail transit in first-tier cities such as Beijing and Shanghai was stable at 11.5-12.5 million passengers. China has become the country with the world's largest rail transit system, according to the indicators of the total length of the lines and the annual passenger traffic [1]. China's metro system has responded to the rising passenger traffic through high-load, high-frequency operation. This high-density operation, combined with the complexity of the internal environment of the metro system and the uncertainty of the external environment, has greatly increased the possibility of accidents and disasters in the operation phase. These incidents include train failures, fire accidents, terrorist attacks, natural disasters, and system floods [2]. It is worth noting that these unexpected events, when they occur in a metro system, will inevitably lead to the large-scale clustering of people in metro stations, posing emergency evacuation risks and a serious threat to public safety.

The existing research on metro emergency management is mainly based on accident analysis. By analyzing the various types of operational accidents that have occurred in the past, corresponding preventive measures and emergency plans are proposed. This "post-event" and "passive" safety management mode is largely reactive and cannot prevent accidents in advance [3]. As an emerging safety management mode that is "preventive" and "proactive", the DFS concept provides a theoretical basis for reducing the emergency evacuation risks in metro stations in the design phase. The DFS concept and related pre-control measures have been validated through correlations between design and safety incidents [4-7]. However, there is no systematic summary or classification of DFS pre-control measures for emergency evacuation in metro stations. In this scenario, designers are likely to neglect the fragmented DFS pre-control measures scattered across massive design specifications, and the latest DFS pre-control measures cannot easily be incorporated. Furthermore, the literature lacks an evaluation of the effect of a design scheme, especially for evacuation design, on reducing the emergency evacuation risks in metro stations. This limits the optimization of design to achieve safer emergency evacuation. Therefore, this research aims to propose a DFS application method that integrates identifying DFS pre-control measures and evaluating the evacuation design effect.

With the development of information technology, the popularity of BIM technology in the engineering and design industry provides an opportunity for the practice of the DFS concept. However, the existing joint applications of the DFS concept and BIM technology are mainly focused on the construction phase of engineering projects, whereas such has often been neglected in the operation phase [8]. More specifically, safety design tools based on the BIM platform for emergency evacuation have rarely been developed. The existing research generally converts DFS pre-control measures into safety rules that can be identified by the BIM platform, enabling the input inspection of design schemes [9]. However, whether the overall design after the input inspection is safer has not been confirmed on the BIM platform. Therefore, the evaluation of the effectiveness of the DFS pre-control measures needs to be included in the BIM platform.

Considering that the automation application of the DFS based on the BIM platform offers extensive application prospects in the safety evacuation design of metro stations, this study elaborates upon the abstract DFS concept and describes the “D” in DFS as “equipment and facility selection and layout design”, while the “S” represents “emergency evacuation safety”. By means of pre-control measures applied in the process of equipment selection and layout design, the metro stations’ administrators could minimize the evacuation safety risk and avoid the inherent defects of layout design, such as a low evacuation efficiency, numerous evacuation bottlenecks and so on. At the same time, to make the DFS more designer-friendly, the pre-control measures are converted into safety rules that can be recognized by the BIM platform so that the designer can automatically make a real-time judgment whether the current layout design can ensure emergency evacuation safety. To summarize, this study aims to (1) establish a complete DFS application method including the identification of pre-control measures and evaluation of the design effects; (2) develop a safety evacuation design toolbox (SEDT) based on the BIM platform to facilitate designers implementing the goal of DFS conveniently throughout the entire design phase; and (3) conduct a case demonstration to verify the use functions and application effects of the SEDT. Our proposed method integrating DFS pre-control measures and the evaluation of the evacuation design effect with specific design processes, its implementation on the BIM platform, and its validation through a case will contribute to the continuous optimization of design schemes and the reduction of risk in emergency evacuation.

2 Literature review

2.1 Review of DFS application methods for the evacuation of metro stations

The concept of DFS is derived from the theory of the hierarchy of controls and the Szymeberski curve [10,11]. It refers to the consideration of the safety of construction workers, operators and project end users in the design stage during the construction project life cycle, eliminating or reducing safety risks through normalized and improved design. A research on metro safety incidents shows that 36.1% of safety incidents in the construction phase and 69.9% of safety incidents in the operational phase are related to design [12]. Therefore, taking operational safety risks into consideration during the design stage can significantly improve the safety performance of a metro system. A metro system is a semi-open, confined and crowded space; once an emergency occurs, emergency evacuation will be initiated by the stations. Highly efficient emergency evacuation minimizes economic losses and casualties. The existing studies found that the emergency evacuation of metro stations is mainly influenced by three aspects: (1) people, such as passenger evacuation behavior [13,14]; (2) objects, such as the equipment facility evacuation capacity and layout of equipment and facilities [15,16]; and (3) human-object interactions, such as the evacuation routes of passengers between walking facilities [17,18]. To reduce the emergency evacuation risks generated by the above influences, the existing studies proposed measures for optimization design, such as in terms of passengers, escape plans to reduce the congestion probability, and rescue plans to improve the emergency response efficiency [19,20]. In terms of equipment and facilities, the existing studies proposed how to add and adjust mobile service facilities and sign facilities under different situations of passenger flows [21,22]. It is not difficult to find that the existing design pre-control measures still focus on the design of the real-time control plan of the risk when an emergency evacuation occurs, and little attention is paid to the inherent defects of the layout design of metro stations. To achieve the advanced pre-control of emergency evacuation risks, it is necessary to focus on the selection and layout design of equipment and facilities.

Furthermore, the literature lacks a comprehensive evaluation of design schemes, especially for evacuation design. Therefore, to reflect the effectiveness of DFS pre-control measures in reducing the emergency evacuation risks in the operation of metros, it is necessary to evaluate the evacuation design effect. In the existing studies, the number of evacuated people and evacuation time were generally used as indicators to evaluate the evacuation efficiency. The number of evacuated people can reflect the traffic capacity of the equipment and facilities, and the evacuation time can reflect the rationality of the evacuation route formed by the equipment and facilities [16]. These two types of evaluation indicators are mainly retrieved via an emergency evacuation-based simulation on the layout design. The simulation methods mainly consist of mathematical computations and computer simulations [23]. (1) Through calculation formulas, mathematical computations mainly provide evaluation indexes of specific evacuation effects. For example, the limit state equation is used to display passengers' response time, behavior time and movement time to an exit during emergency evacuations [24]. Via a data envelopment analysis and genetic algorithms, the station service capacity can be computed [25]. (2) The computer simulation method incorporates the behavioral characteristics of the passengers into the evacuation model from a microscopic perspective and obtains the optimal evacuation path through the simulation of passenger behavior. The commonly used methods include cellular automaton based simulations and agent-based simulations. The cellular automaton has less relativity with personnel themselves, basically establishing rules for the movement of personnel in metro stations. It generates high homogeneity among personnel while overlooking individual differences. To maintain individual differences, many scholars adopt the agent-based modeling method to refine the model [26]. Some studies have compared mathematical computations with computer simulations through a case analysis. It is found that although the computer simulations can better reflect the details of the evacuation process, mathematical computations can identify the most critical equipment and facilities and the most unfavorable evacuation scenarios in a more precise and efficient way, which directly contributes to the inspection and optimization of the layout design and avoids inconvenient changes to the established metro station models in the evacuation software [23].

It is worth noting that, according to the bucket theory, the effect of emergency evacuation at metro stations depends critically on the evacuation weak points of the design, i.e., the evacuation bottlenecks [27]. At the same time, because the evacuation route of passengers is composed of passageways, automatic ticket gates, stairways, escalators, platforms and other walking facilities that affect the flow of passengers, the walking facilities are common bottlenecks in the design scheme [28]. The accurate screening of the bottlenecks can also provide a reference for the planning of evacuation routes in the emergency plan for the metro station operation phase. Therefore, the metro station design scheme should not only meet the basic requirements such as the number of evacuated people and evacuation time but also screen the evacuation bottlenecks in the existing layout to further optimize the design. At present, the screening of the existing evacuation bottlenecks is still primarily used to optimize the emergency plan for completed metro stations. By importing the monitoring data of the passenger flow into the evacuation simulation software for emergency evacuation simulation and screening out the walking facilities with high congestion probability, more targeted emergency evacuation guidance could be formulated [29]. Therefore, to perform the screening of evacuation bottlenecks to contribute to the safe design of metro stations, it is necessary to construct a mathematical model of the “route-planning behavior” and “queuing behavior” of passengers in the existing layout design of equipment and facilities. Embedding the model into the BIM design software of metro stations would be helpful for designers to avoid emergency evacuation risks in a timely manner during the design process. It is concluded that there are three main shortcomings in the existing DFS studies on metro stations: (1) The existing pre-control measures to achieve the goal of DFS were mainly derived from accident cases and design specifications, from which safety rules were established [30,31]. However, most of the identified DFS pre-control measures lacked a correlation analysis between the specific design content and specific safety risk, which caused designers to be unclear about the process and effect of applying pre-control measures; (2) The existing DFS application methods mainly focus on the knowledge management of pre-control measures, with no standardized identification method or evaluation method of the evacuation design effect [32,33]. At the same time, the existing methods for calculating the evacuation efficiency based on dynamic evacuation simulation are generally based on established metro station models, and then emergency plans could be formulated and optimized, making it difficult to change the layout design when the evacuation effect does not meet the requirements [34]; (3) The existing technology to realize DFS is mainly to store the pre-control measures in the form of a database. The effect of safety design depends on the designers' independent queries to the database after the completion of the design scheme, which reduces the reliability and operability of the safety design [35]. Therefore, to address the above deficiencies, this research refines the concept of DFS, focusing on the selection and layout design of equipment and facilities in metro stations for emergency evacuation safety, and constructs a standardized DFS application method that includes the identification of DFS pre-control measures and the evaluation of the evacuation design effect. Among them, the evacuation design effect evaluation method overcomes the defect of the existing research of a lack of verification of the safety design effect. At the same time, this study uses mathematical calculation and queuing theory modeling to verify the evacuation efficiency and identify evacuation bottlenecks. It is convenient for designers to intuitively avoid emergency evacuation risks in the design process and to improve upon the passive safety management concept of the existing evacuation research that emphasizes the optimization of emergency plans while ignoring the inherent defects of the layout design. Finally, the automated SEDT developed via the BIM platform commonly used by designers is used to improve the effectiveness and efficiency of the emergency evacuation safety design for metro stations.

2.2 Review of BIM tool development for safety design

BIM is frequently used for safety design in engineering projects due to its powerful data integration and visual modeling capabilities [36]. Guo et al. [37] established construction safety rules and associated these rules with the components of the BIM model to automatically detect safety issues in design. Malekitabar et al. [38] identified five groups of safety risk drivers in the design stage by analyzing 363 construction accidents and used automatic detection to determine whether the existence, type, and distance of the model components corresponding to each risk driver in the BIM model meet safety requirements. Currently, in most safety design tools, BIM models are integrated with various types of decision-making software using the secondary development technique of the BIM platform. The safety design tools automatically extract building information from the BIM models and import the information into different types of decision-making software to optimize the safety performance of the design scheme. The extraction of building information in the BIM model can be approached in two ways. The first way is to directly export the BIM model to other software in the Industry Foundation Classes (IFC) format for safe design decisions [8,39]; the second way is to call and process the data through the secondary development technique of the BIM platform when extracting the building information and in this way to synchronously realize safety design decisions in the model [40,41]. Existing studies that combine the BIM platform with other decision-making software to achieve safety design include the integration of the BIM platform and database software, the construction of BIM plug-ins that contain accident databases to express the safety risk knowledge at the pre-construction stage [42], the integration of the BIM platform and geographic information system (GIS) software to simulate disasters with spatiotemporal characteristics in the design schemes [43], the integration of the BIM platform and MATLAB software to avoid space conflicts in the operation of various large equipment for construction site layout design [44], and the integration of the BIM platform with finite element analysis software to guarantee the reliability of the engineering structure design [45]. In summary, to expand the BIM model safety management information, tools are applied to provide designers with supplementary case information, geographic location information, maintenance information, etc. [41,46]. However, corresponding optimized suggestions and feedback on designs based on designers' work flows could not be provided.

Currently, safety design tools based on the BIM platform for emergency evacuation have rarely been developed [12]. The existing studies generally import BIM models into pedestrian evacuation software for emergency evacuation simulations [47]. However, such methods have extremely stringent requirements for the compatibility of the pedestrian evacuation software and tend to lose building information during the import process, which increases the workload associated with the secondary modeling. Moreover, the development of safety design tools that rely on off-the-shelf pedestrian evacuation software is difficult and computationally inefficient. Therefore, to encourage metro station designers to proactively consider safe evacuation pre-control measures when drawing design schemes, designers should be provided with functional plug-ins integrating various safety design requirements that can be used directly in the BIM platform. In this way, safety design can be achieved by running the appropriate plug-ins. Therefore, this study develops an SEDT directly embedded into Revit software to make the interaction of "designer-BIM model-DFS plug-ins" clear and convenient. When designers encounter problems in constructing BIM models, the designer can click SEDT, which can feedback problems in the design interface of the BIM model in time to ensure the safe and reliable effect of the selection of equipment and layout design.

The existing BIM plug-ins for safety design mainly have two shortcomings: (1) each function plug-in does not correspond to the design flow, and a large number of DFS pre-control measures are directly placed into the plug-in in the form of a database without classification [37]; this not only is not conducive to the update and visualization of the DFS pre-control measures but also easily confuses designers regarding in which specific design task to use the plug-in. (2) There is a lack of a design effect check on the design scheme generated by the application plug-in on the BIM platform. Most studies used the expert interview method to verify the validity of the safety design plug-in but did not perform any objective evaluation of the design effect [48]. Therefore, to improve the efficiency of designers in applying BIM plug-ins, this research systematically classifies DFS pre-control measures and makes them correspond to specific design processes to form a BIM toolbox SEDT with multiple safety design functions. To verify the application effect of the BIM plug-ins, this research directly built the evacuation design effect evaluation indicators into the toolbox and automatically evaluated the evacuation efficiency and evacuation risk of the overall design scheme, which helps the design scheme be continuously optimized and ultimately safer. Meanwhile, to show the operability of the SEDT and the improvement in the layout design, this study is based on the real case of the Chinese metro station X and shows how the SEDT application can help designers complete and optimize the selection and layout of metro station X in terms of equipment facilities during the design process.

3 Research methods

To achieve the selection and layout design of equipment and facilities in a metro station for optimizing the emergency evacuation safety, a systematic methodological framework is proposed in Fig. 1. Phase 1 is concerned with establishing a general DFS application method for emergency evacuation in metro stations, including the construction of a systematic identification method for DFS pre-control measures (Step 1) and a comprehensive evaluation method of the evacuation design effect (Step 2). In phase 2, this research will automate the DFS application method based on the BIM platform and develop a multifunctional SEDT (Step 3). When the designer completes the structural design of metro stations on the BIM platform, the selection and layout design of the equipment and facilities are required. At this time, the designer can utilize the SEDT built into the Revit software for auxiliary design when adding and laying out equipment in the BIM model, which ensures that there is no emergency evacuation risk in the layout design, to achieve the effect of DFS implementation.

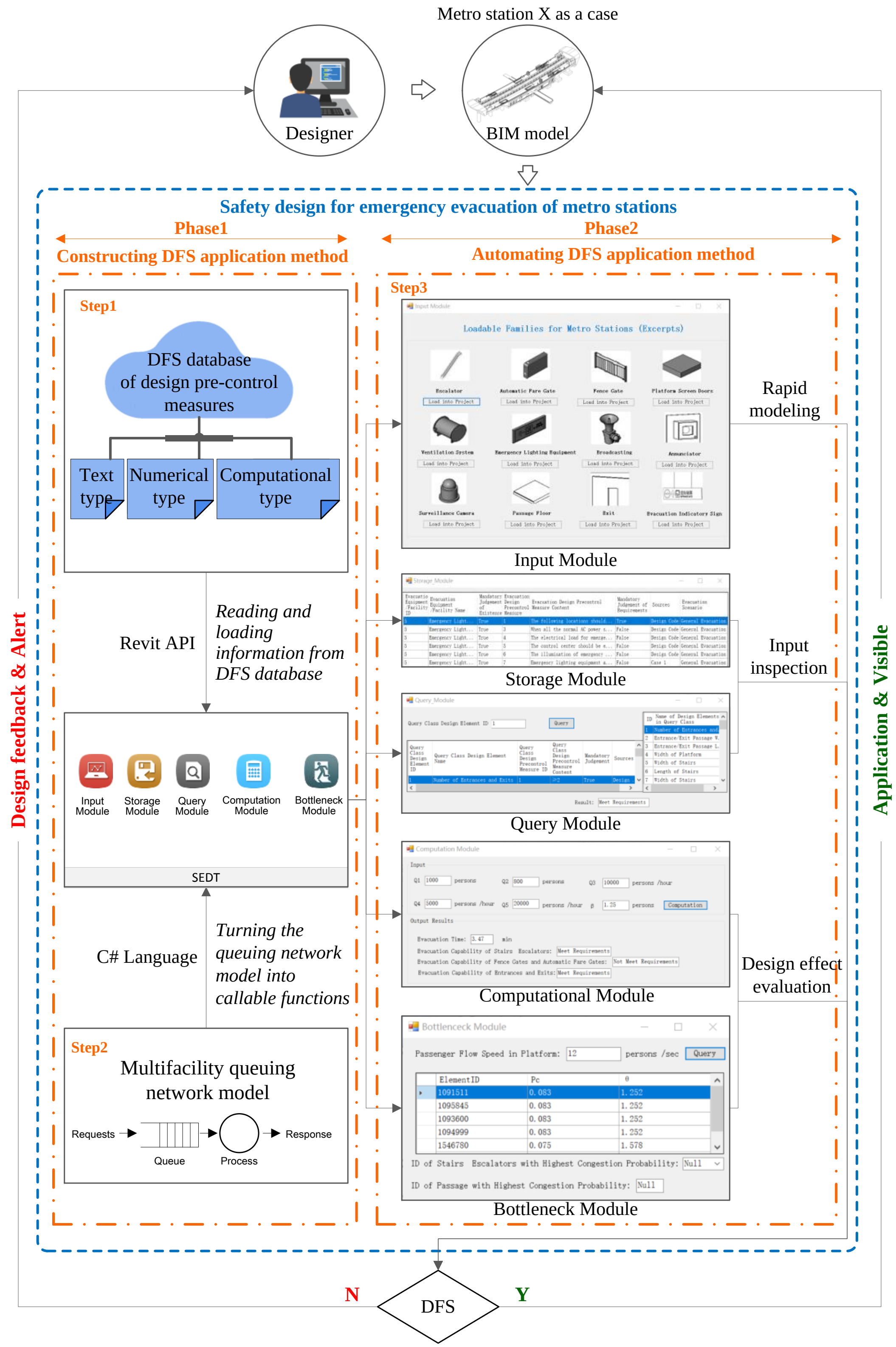

Fig. 1. Methodological framework.

Step 1 aims to establish the standardized identification criteria and a classification system for DFS pre-control measures based on the DFS concept to systematically identify fragmented DFS pre-control measures scattered in data sources such as national codes, accident cases and journal documents to form the DFS database [49] and to provide a theoretical basis for the safety design of the selection and layout of individual equipment and facilities in metro stations. The details of Step 1 are provided in Section 3.1.

Step 2 aims to construct an evaluation method that comprehensively reflects the evacuation design effect of the metro station; based on the traditional evacuation efficiency evaluation indicators (traffic capacity and evacuation time) [50], the evacuation bottleneck indicators are calculated based on the multifacility queuing network model to reflect the evacuation risk and provide an objective assessment of the effectiveness of the DFS pre-control measures and facilitate the continuous optimization of design options. The details of Step 2 are provided in Section 3.2.

Step 3 aims to provide designers with convenient and automated safety design tools through the secondary development technique of the BIM platform. The five plug-ins of input, storage, query, computational and bottleneck modules are formed into the SEDT through the Revit API (it is used to read and load the information of the DFS database constructed by Step 1 in the BIM model) and C# function programming (it is used in the BIM model to implement the multifacility queuing network model built by Step 2 into a function file that can be directly called), which is built into Revit, enabling designers to rapidly perform the modeling in the preliminary design stage, input inspection in the basic design stage, and design effect evaluation in the detailed design stage. The contents of the storage, query and calculation modules stem from the textual, numerical, and computational types of pre-control measures in the DFS database constructed in Step 1, and the operating principle of the bottleneck module comes from the multifacility queuing network model constructed in Step 2. It is necessary for designers to click on the SEDT when laying out each piece of equipment and facility in the BIM model, which is created by the secondary development of Revit software. When clicking it, the corresponding safety design notifications would pop up on the Revit interface, providing designers with pre-control measures, parameter inspections, evacuation efficiency calculation results and feedback so that the final BIM model built by the designer meets all safety design rules in the SEDT. The details of Step 3 are provided in Section 3.3.

This study selects the Chinese metro station X as a case; it is a two-story elevated island station containing a platform and a station hall. The layout design includes all the typical walking facilities involved in all evacuation design schemes, such as stairways, escalators, passageways, gate units, and fence gates. This study demonstrates the application process and operability of the SEDT by employing the SEDT in the equipment and facility selection and layout design. When designers use the SEDT output design scheme in all stages of the entire design phase, if the DFS pre-control measures or design effect evaluation indicators are not met, the SEDT will alert the designer on the interface of each module and assist the designer in continuously optimizing the design scheme until the goal of DFS is reached. The details of this case application are described in Section 4.

3.1 Identification method of DFS pre-control measures

The selection of equipment and facilities and the layout design are decisive factors that affect the evacuation risks at metro stations [51]. The main targets of metro station design schemes are civil construction facilities and various types of equipment, and passengers rely on these equipment and facilities when selecting a specific evacuation route during the evacuation process. Based on the DFS concept, this research establishes an identification method of DFS pre-control measures for the selection and layout design of equipment and facilities in metro stations. Through the standardized retrieval, selection, identification and coding of DFS pre-control measures, the fragmented safety design knowledge is formed into a systematic DFS database to realize the safety design of individual equipment or facilities.

To fully identify the equipment and facility design elements that cause or aggravate the risks associated with emergency evacuation and obtain corresponding DFS pre-control measures, this research used the national codes issued by the China State Bureau of Technical Supervision, accident cases (metro operation accidents with stampedes that were reported by official news websites), the periodical literature (the subject search terms were “metro evacuation”, “metro station layout”, and the names of various facilities inside the metro station that are included in the Web of Science core collection from 2008-2018) as data sources for identifying emergency evacuation DFS pre-control measures for metro stations. The judgment criteria for the DFS pre-control measures include the following three types:

(1) *Criterion I*: Equipment and facilities that should be present but are missing. For example, in the design scheme, the emergency lighting system specified in *Code for design of metro* [52] is missing.

(2) *Criterion II*: The existing equipment and facilities do not meet mandatory requirements. For example, the *Code for safe evacuation of metro* [53] stipulates that the period for which the emergency lighting system is activated should not be shorter than the emergency evacuation time.

(3) *Criterion III*: Although the existing equipment and facilities meet the mandatory requirements, there is still room for improvement and optimization. For example, there is no mandatory requirement for the

arrangement of automatic ticket gates; however, a horizontal layout facilitates the emergency evacuation of passengers from a metro station [54].

The above three categories of standards ensure that the DFS database can be updated according to a certain standard with the updating of national regulations, the accumulation of accident cases, and the development of relevant technologies in journal articles, and the situation in which different designers obtain different design pre-control measures will not occur. The maintenance efficiency of the open source DFS database is thus improved. According to the above three types of criteria, the DFS pre-control measures referenced in national codes, accident cases, and the periodical literature are identified and extracted. The identification process of design pre-control measures based on the DFS concept is shown in Fig. 2.

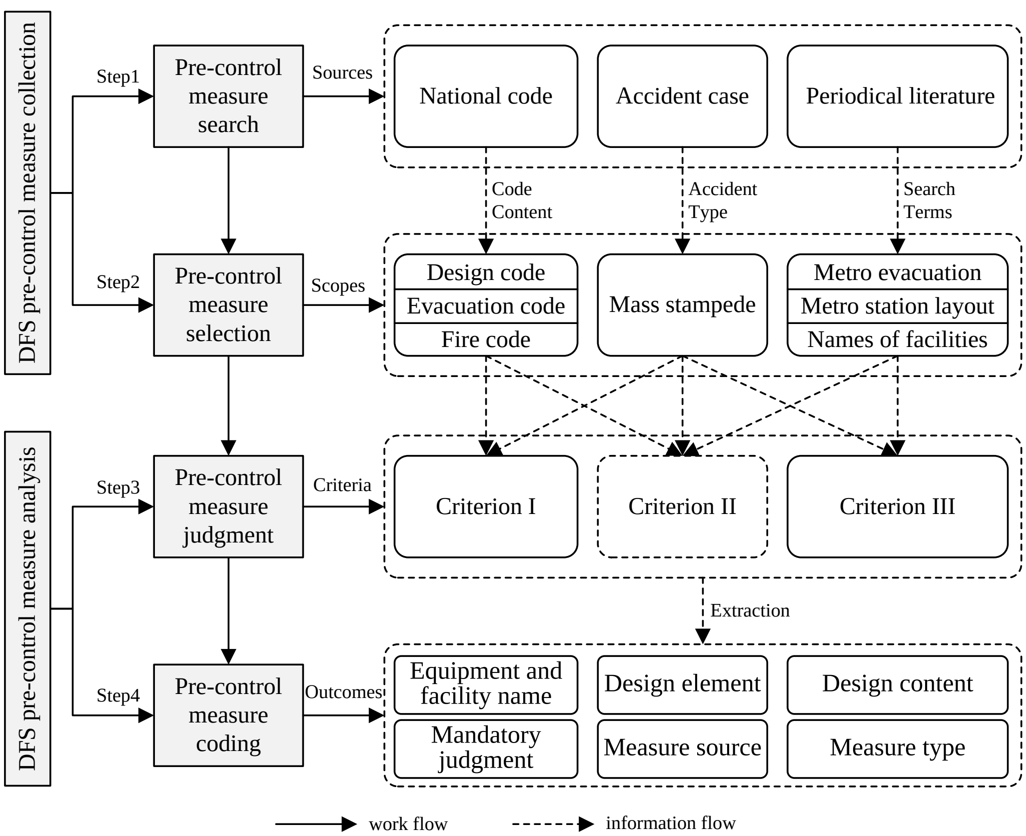

Fig. 2. DFS pre-control measure identification process based on DFS concept.

According to the process shown in Fig. 2, the equipment, facilities, design elements and relevant DFS pre-control measures that affect the emergency evacuation risks can be identified and used to provide guidance for metro station designers in the preliminary design and basic design stages. Specific DFS pre-control measures are listed in Table 1. To transform all DFS pre-control measures into safety rules that can be automatically identified by the BIM platform, the DFS pre-control measures are divided into numerical, computational, and textual types. The numerical type refers primarily to the requirement that the design elements in the pre-control measures yield results that fall within certain numerical ranges; these can be tested to determine whether the elements meet the evacuation requirements by identifying the corresponding design elements in the BIM platform. The computation type mainly refers to the need to meet the calculation formulas provided in the national codes. The textual type mainly refers to pre-control measures expressed in words; that is, formulas and numbers are not involved (only plain text information).

Table 1. DFS pre-control measures for emergency evacuation safety (excerpt).

No.1	Equipment and facility name	No.2	Design element	No.3	Design content	Mandatory judgment	Measure source	Measure type
1	Entrance/exit	1.1	Number of entrances/exits	1.1.1	The number of entrances and exits to each floor in public area is no less than two.	Yes	Evacuation code	Numerical
		1.2	Entrance/exit width	1.2.1	The reasonable width for an entrance or exit of a metro station is 4-7 m.	No	Literature	Numerical
2	Entrance/exit passage	2.1	Entrance/exit passage width	2.1.1	Minimum width is 2.4 m.	No	Design code	Numerical
		2.2	Inside an entrance/exit passage	2.2.1	In a passage with high passenger flow, a separating wall can be set, and the shape of the passage can be modified into a funnel shape to reduce congestion.	No	Literature	Textual
3	Stairways	3.1	Stair arrangement	3.1.1	The distance between an exit ticket gate and a stairway should be no less than 5 m.	No	Design code	Numerical
				3.1.2	The distance between an escalator and a stairway should be no less than 12 m.	No	Design code	Numerical
4	Escalator	4.1	Number of escalators	4.1.1	The formula should be satisfied.	Yes	Design code	Computational
		4.2	Escalator type	4.2.1	The inclination angle of the escalator at the station entrance and exit should not exceed 30°, and the inclination angle of the escalator from the platform to the station hall should be 30°.	No	Design code	Numerical
5	Fence	5.1	Fence height	5.1.1	The separation between the paid zone and the free zone should be a see-through fence of no	No	Design code	Numerical

					less than 1.1 m, and a side-hinged gate that opens in the direction of evacuation should be provided.			
		5.2	Fence gate width	5.2.1	The formula should be satisfied.	No	Design code	Computational
6	Automatic ticket gate	6.1	Automatic ticket gate arrangement	6.1.1	The distance between an exit ticket gate and a stairway should be no less than 5 m, and the distance between an entrance ticket gate and a stairway should be no less than 4 m.	No	Evacuation code	Numerical
				6.1.2	The automatic ticket gate should adopt a horizontal arrangement to effectively reduce pedestrian entry and exit times.	No	Literature	Textual
7	Emergency lighting	7.1	Emergency lighting layout	7.1.1	Emergency lighting should be installed in the station hall, platforms, escalators, moving walkways, stairways, evacuation passages, safety exits, section tunnels, station control rooms, substation duty rooms, power distribution rooms, signal equipment rooms, fire pump rooms, and public security rooms.	No	Evacuation code, Metro operation safety evaluation standard	Textual
		7.2	Emergency lighting system power supply	7.2.1	Emergency lighting facilities and signs should be connected to a dedicated power supply for fire emergencies or have self-contained power storage functionality.	No	Case 1, Case 7	Textual

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3.2 Evaluation method of evacuation design effect

The authors of this research believe that the complete DFS application method should include the identification method of DFS pre-control measures and the evaluation method of the evacuation design effect. Therefore, after applying the DFS pre-control measures for the selection and layout design of the equipment and facilities in metro stations, the evaluation of the evacuation design effects can objectively reflect whether the design scheme implements DFS. The evaluation indicators for the evacuation design effect constructed in this research include evacuation efficiency indicators and evacuation risk indicators. Among them, the evacuation efficiency indicators include the traffic capacity of each walking facility and the passenger evacuation time under the overall design scheme. There is a clear calculation formula provided in the *Code for design of metro* [52], but the evacuation risk indicator, that is, the computation method of the congestion probability of the evacuation bottleneck, has not yet been unified. The common evacuation simulation models can be divided into dynamic models (for example, lattice gas models, agent models, and social force models) and static models (for example, queuing theory models and minimum-cost maximum-flow models). The dynamic models focus on pedestrian characteristics, and the static models focus on pedestrian density and the station layout [51,55]. Although the current research on the crowd evacuation capacity is relatively rich, studies on evacuation, which takes the spatial connections of stairways, passages and other facilities into consideration from the perspective of the layout design of metro stations, are rare [51]. Hence, based on the goal of optimizing the layout design of equipment and facilities, this research uses queuing theory to construct bottleneck possibility indicators for equipment and facilities and to calculate the probability of the congestion of metro stations at specific passenger traffic levels [15].

Considering that this study focuses on whether the selection and layout design of walking facilities will cause evacuation bottlenecks, a separate simulation is not performed on pedestrians' walking speeds with different passenger flow characteristics. In this study, the fitting results of existing studies on the walking speed of pedestrians in Chinese metro stations were directly adopted, obtaining the speed-density function of pedestrians between stairways, passageways and other walking facilities [16]. Finally, after checking the congestion of each walking facility in all evacuation paths, the walking facilities that show a high likelihood of congestion are set as the evacuation bottlenecks so that the designer can clearly know what walking facilities require further optimization in the design scheme. The specific screening method for evacuation bottlenecks is as follows.

3.2.1 Step 1: Construct a single-facility queuing model for metro stations and obtain bottleneck indicators for the walking facilities

When crowding and moving in the walking facilities of metro stations, pedestrians tend to queue or congest as the passenger flow increases. If the metro station space is considered as a large-scale queuing system, the walking facilities can be regarded as the service desk of the system. The movement characteristics of pedestrians are the service characteristics of the system, and these are related to the physical characteristics of the walking facilities and the movement patterns of the pedestrians. The queuing system has the following characteristics: (1) pedestrian arrivals obey a Poisson distribution and are independent of each other; (2) pedestrian density has an impact on the service efficiency, i.e., service efficiency is related to pedestrian status; (3) the pedestrian density in the same types of spaces (stairways and passageways) is assumed to be equal in all areas – each walking facility can be regarded as a service desk, and the service times are independent and identically distributed; (4) the system space is limited, and infinite queuing is not allowed; and (5) the service rules are "first come, first served". The above characteristics are consistent with the assumptions of the M/G/c/c model [56,57]. Therefore, that model is used in this research to construct a single-facility queuing system model for metro stations.

The M/G/c/c model is a state-dependent queuing network model. Many scholars adopted this method to analyze the queuing service characteristics and congestion probability of a single facility in a dynamic environment [58,59]. The probability p_n of having *n* pedestrians in a walking facility is calculated as follows:

$$p_n = P_r\{N = n\} = \left\{\frac{[\lambda E(T_1)]^n}{n!\, f(n) f(n-1) \cdots f(2) f(1)}\right\} p_0,\ \ n = 0,1,2,\cdots,c$$

The variables that appear in this equation are defined as follows:

λ: Pedestrian arrival rate at the entrance to the facility (person/s);

N: Number of passengers in the facility;

n: Actual number of pedestrians in the facility;

$f(n)$: Service rate of *n* pedestrians in the facility, $f(n) = \frac{V_n}{V_1}$, where V_1 is the average travel speed for one passenger in the facility $(\mathrm{m/s})$ and V_n is the average travel speed when *n* passengers are in the facility $(\mathrm{m/s})$. Considering that this research studies emergency evacuations, the acquisition of V_1 and V_n values requires the correction of the velocity-density function under normal evacuation conditions [60]. The differences and uncertainties in the behavior and psychology of different passengers generate different walking speeds in walking facilities [61]. Hence, the results of the fitting based on the Chinese metro station case are used as the walking speeds in passageways and on stairways [16]. What is noteworthy is that the metro station designer can fit the walking speed data according to the operational data of the local passenger flow, which makes the cited data consistent with the common behavior characteristics of local passengers.

$E(T_1)$: Expected service time for a single pedestrian in the facility, $E(T_1) = \frac{l}{V_1}$, where l is the facility space length (m);

p_0 : Probability that no pedestrians are in the facility, $\text{i.e.}, P_r\{N = 0\} = \left\{1 + \sum_{i=1}^{c} \frac{[\lambda E(T_1)]^i}{i! f(i) f(i-1) \cdots f(2) f(1)}\right\}^{-1}$, where c is the capacity of the walking facilities (number of people), which can be calculated by $c = [klw]$ ($[x]$ indicates an integer no greater than x, k is the pedestrian density in the walking facility (persons/m^2), and w is the walking facility space width (m)).

In this research, the computation formula in the model for identifying a bottleneck indicator in the walking facility is as follows:

$$p_c = p_r[N = c]$$

$$\theta = \lambda(1 - p_c)$$

$$L = E(N) = \sum_{i=1}^{N=c} i p_i$$

$$W = E(T) = \frac{L}{\theta}$$

The variables in the equations above are:

p_c: Probability of traffic congestion (arriving pedestrians exceeding the walking facility's capacity);

θ: Number of people output per second, that is, the output rate (persons/s);

L: Expected number of passengers in the walking facility, i.e., $E(N)$;

W: Service time expected by the passengers, i.e., $E(T)$, s.

3.2.2 Step 2: Construct a multifacility queuing network model for metro stations and calculate the probability of traffic congestion

In the state of emergency evacuation, when the evacuated passengers fail to immediately pass through walking facilities such as stairways, escalators and passages due to congestion, they will queue up and wait for evacuation service. After passing through single-facility queuing models composed of walking facilities, the evacuated passengers can finally reach the safe area to complete the entire emergency evacuation service [62]. Hence, from the network point of view, the walking facilities in the metro station are nodes in the network, and the spatial relationships between the facilities are the edges in the network. Based on the different connections between walking facilities with spatial continuations, the transitive relations between the pedestrian output rate and arrival rate on the walking facilities can be reflected, thus constructing a multifacility queuing network model for metro stations. The specific construction contents are as follows:

(1) *Node Set*: The nodes in the topology of the multifacility queuing network model include three types: source nodes, intermediate nodes and terminal nodes. ① The source node is the start of the evacuation. This study takes no account of specific emergencies, focusing on the most unfavorable evacuation conditions of metro stations. The platform, which is the farthest area from the safety exit, is the place from where the evacuation starts. ② The intermediate node refers to all types of walking facilities. It is characterized by covering both the pedestrian input and output during the evacuation, the overall volume of which is conserved. During the emergency evacuation of metro stations, escalators can be treated as stairways, for escalators stop running. Given that the automatic ticket gates stay open, the pedestrian speed and density of channels between the automatic ticket gates are similar

to those of the passageways, so the automatic ticket gates can be treated as passageways in the emergency evacuation. Due to the different evacuation capabilities of different types of walking facilities, congestion is most likely to occur at intermediate nodes, creating evacuation bottlenecks.

③ The terminal node is the exit of the metro station, which is characterized by only covering the pedestrian input but no output. For passengers themselves, reaching the node is regarded as being successfully evacuated. Each node has its own inherent properties, including two main aspects. One is the geometric dimensioning and layout position of the node, and the other is the node capacity and traffic capacity. The node set is the basis for setting relevant parameters and the basic conditions for solving the model during modeling. When performing modeling, the node set is the basis for setting relevant parameters and provides the basic conditions for the model resolution.

(2) *Edge Set*: The edges in the multifacility queuing network model are directed edges, indicating the physical connections between the various walking facilities in metro stations, which form the route for pedestrian evacuation. In this study, all passengers' walking directions in the evacuation default to the direction of the security exits without passenger flow conflicts. To identify the evacuation bottlenecks under the overall layout design, it is necessary to identify all the evacuation paths formed by the existing layout design of the walking facilities. In this study, the Depth-First-Search algorithm is used to realize the automatic search for evacuation paths in the multifacility queuing network model. The algorithm is to establish a set for each node in the model, which stores all nodes directly connected to the node (excluding the node itself). Then, all the paths in the topology network structure are traversed through the algorithm, and the result is saved when the complete path is searched. The algorithm

traverses all routes in the network topology, and the results are saved when the intact route is searched [63].

Since the focus of this study is to identify which walking facility is the evacuation bottleneck in the existing equipment and facility layout design, a simplified metro station is selected, including a platform (Node A), an exit (Node B), 5 escalators (Nodes 1-5) and 2 channels (Nodes 6-7), creating a queueing network diagram of metro station equipment facilities, as shown in Fig. 3. Ten effective evacuation routes in the walking facility network are stored through an adjacency list. The storage structure of the adjacency list is shown in Fig. 4. The extension of the single-facility queuing model to the multifacility queuing network model of metro stations needs to highlight the selective probability of the node. This study assumes that the attraction of similar walking facilities to pedestrians has a linear correlation with the width of the facility [64]. The correlation between the pedestrian input rate and the output rate of each walking facility is as follows:

$$\theta_i = \lambda_i(1 - p_{ci}),\ i \in \{A, 1,2,3,4,5,6,7, B\}$$

$$\theta_A = \theta_{A1} + \theta_{A2} + \theta_{A3} + \theta_{A4} + \theta_{A5}$$

$$\theta_1 = \theta_{16} + \theta_{17},\ \theta_2 = \theta_{26} + \theta_{27},\ \theta_3 = \theta_{36} + \theta_{37},\ \theta_4 = \theta_{46} + \theta_{47},\ \theta_5 = \theta_{56} + \theta_{57}$$

$$\lambda_6 = \lambda_{61} + \lambda_{62} + \lambda_{63} + \lambda_{64} + \lambda_{65},\ \lambda_7 = \lambda_{71} + \lambda_{72} + \lambda_{73} + \lambda_{74} + \lambda_{75},\ \lambda_B = \lambda_{B6} + \lambda_{B7}$$

$$\lambda_1 = \theta_{A1},\ \lambda_2 = \theta_{A2},\ \lambda_3 = \theta_{A3},\ \lambda_4 = \theta_{A4},\ \lambda_5 = \theta_{A5}$$

$$\lambda_{61} = \theta_{16},\ \lambda_{62} = \theta_{26},\ \lambda_{63} = \theta_{36},\ \lambda_{64} = \theta_{46},\ \lambda_{65} = \theta_{56}$$

$$\lambda_{71} = \theta_{17},\ \lambda_{72} = \theta_{27},\ \lambda_{73} = \theta_{37},\ \lambda_{74} = \theta_{47},\ \lambda_{75} = \theta_{57}$$

$$\lambda_{B6} = \theta_6,\ \lambda_{B7} = \theta_7$$

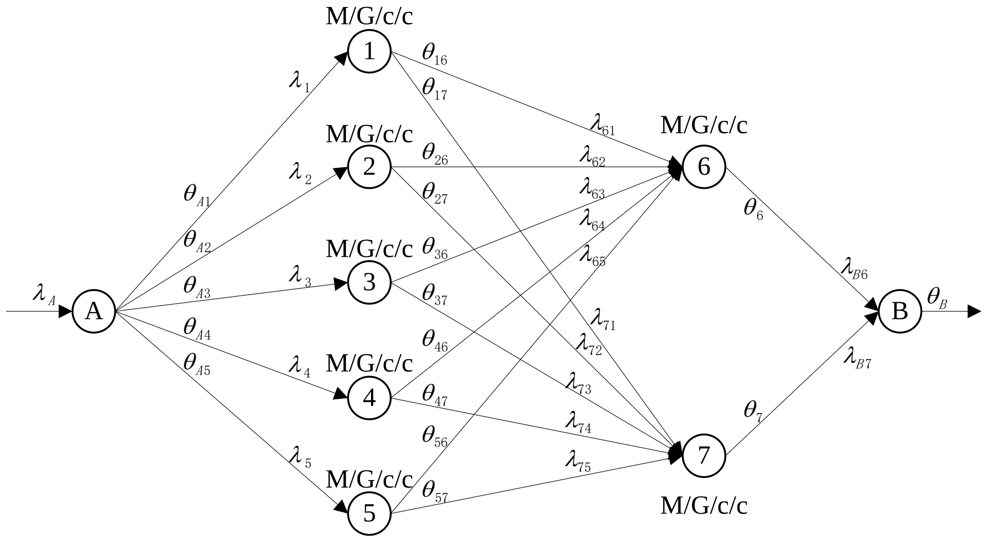

Fig. 3. Schematic diagram of the multifacility queuing network system in the metro station.

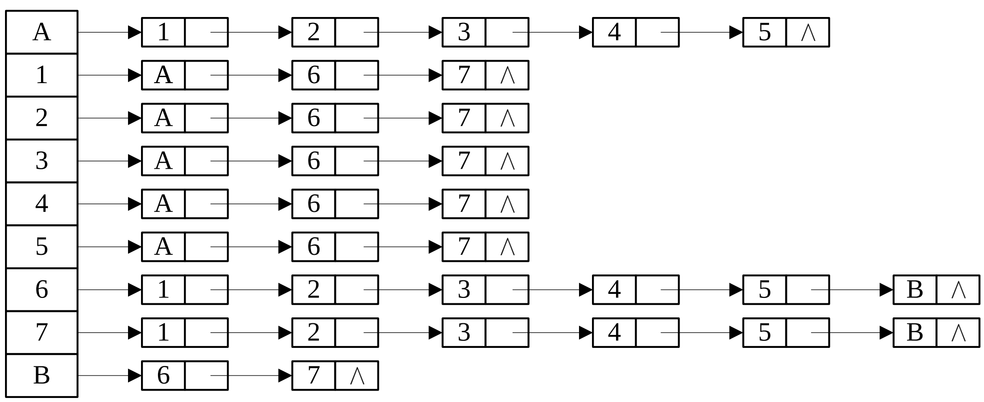

Fig. 4. Storage structure of adjacency list for effective evacuation routes in the network structure.

Based on the multifacility queuing network model of the metro station, after inputting the basic data such as λ, V_n, k, l, and w, the bottleneck indicators p_c, θ, L, and W of the walking facilities can be calculated, and the possibility that congestion will occur in each walking facility can be determined. If the inspection reveals that there is an evacuation bottleneck, the designer can conduct the targeted design optimization of the evacuation bottleneck.

3.2.3 Step 3: Verify the multifacility queuing network model of the metro station and evaluate the accuracy *of the computation method*

AnyLogic is a system simulation software that supports multiple modeling methods. The Pedestrian Library of this software, which is a simulation platform based on the social force model, can be applied to pedestrian evacuation simulations involving various scenarios [65]. To verify the scientific nature of the multifacility queuing network model of the metro station, a simplified two-story island station with two exits and five stairways is selected, and the multifacility queuing network model and AnyLogic simulation software are used to compute and compare the likelihood of bottlenecks. The AnyLogic emergency evacuation model is divided into two parts: the first part, the building model, is shown in Fig. 5, and the geometry of the walking facilities is shown in Table 2; the second part, the process model, is shown in Fig. 6.

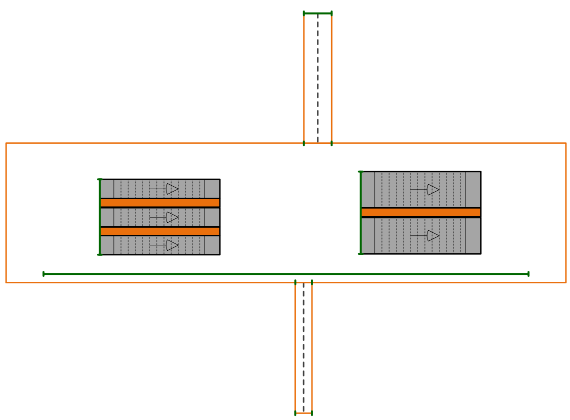

Fig. 5. Top view of the AnyLogic building model.

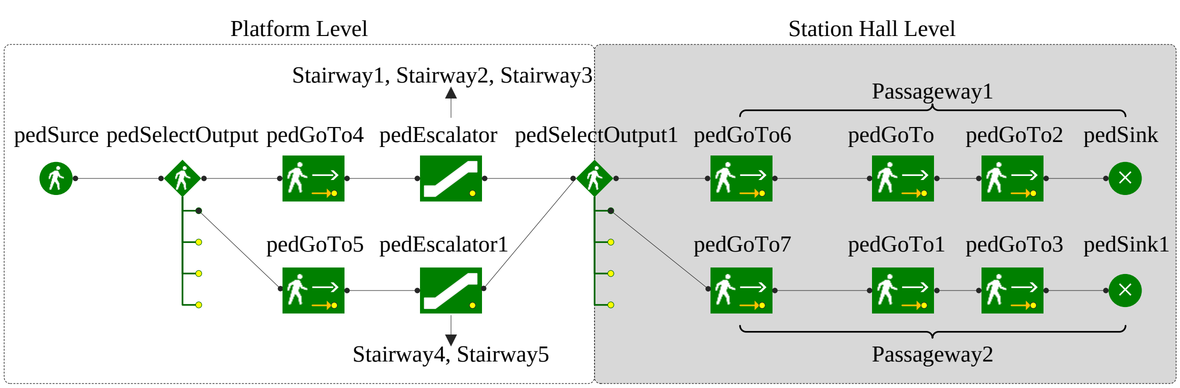

Fig. 6. AnyLogic process model.

Table 2. Geometric dimensions of the walking facilities.

No.	Facility name	*L*/m	*W*/m
1	Stairway 1	6.0	2.0
2	Stairway 2	6.0	2.0
3	Stairway 3	6.0	2.0
4	Stairway 4	8.0	4.0
5	Stairway 5	8.0	4.0
6	Passageway 1	10.0	3.0
7	Passageway 2	10.0	2.0

The process model needs to be associated with the building model. In the AnyLogic property settings, the pedestrian arrival rate λ is set to 13 persons/m, and the maximum number of arrivals is set to 800 persons. After running the model, the flow density of the Platform Level of the metro station during emergency evacuation is shown in Fig. 7, and the flow density of the Station Hall Level is shown in Fig. 8.

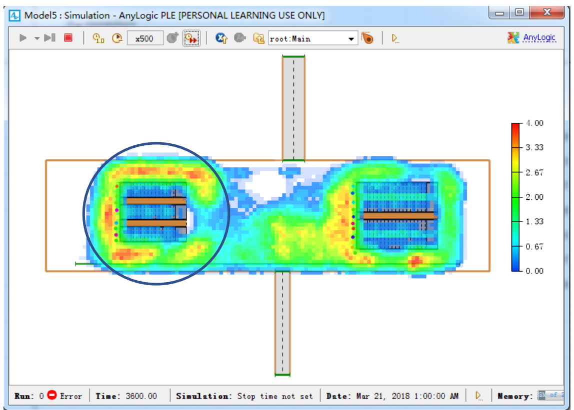

Fig. 7. Detection of the passenger flow density of the platform level.

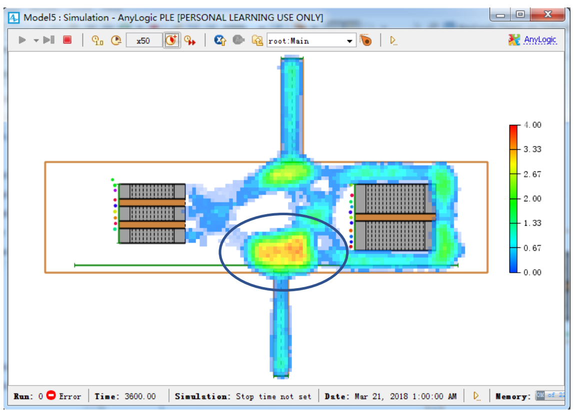

Fig. 8. Detection of the passenger flow density of the station hall level.

Figs. 7 and 8 show that the passenger densities in stairways 1, 2, and 3 are relatively high, reaching 3.3 to 4.0 persons/m^2. The flow rate of people entering passageway 1 is also relatively high, reaching 2.6-3.33 persons/m^2. Therefore, among these facilities, the most likely congestion points are in stairways 1, 2, and 3 and passageway 1. To verify that the queuing theory model can be used for evacuation simulation, basic data such as the pedestrian arrival rate and the geometric parameters of the equipment and facilities in the AnyLogic model are input into the multifacility queuing network model of the metro station, and the multifacility queuing network model of the metro station is then calculated. The results for each bottleneck are shown in Table 3.

Table 3. Computation results of bottleneck indicators for the multifacility queuing network model of metro stations.

No.	Facility name	p_c	θ	$E(N)$	$E(T)$
1	Stairway 1	0.0132	1.833	34,738	18,954
2	Stairway 2	0.0132	1.833	34,738	18,954
3	Stairway 3	0.0132	1.833	34,738	18,954
4	Stairway 4	0.0002	3.713	84,277,764	22,707,842
5	Stairway 5	0.0002	3.713	84,277,764	22,707,842
6	Passageway 1	$8.437*10^{-66}$	7.755	1827	235
7	Passageway 2	$9.656*10^{-27}$	5.170	53,816	10,412

The computation results show that the congestion rates of the stairways are generally greater than those of the passageways and that the probabilities of congestion in stairways 1, 2, and 3 are greater than the those in stairways 4 and 5. In addition, the congestion rate of passageway 2 is greater than that of passageway 1. This result is confirmed by the results of the AnyLogic simulation; therefore, upon identifying the bottlenecks in the design scheme, the queuing theory model is shown to be reasonable and effective.

The evaluation method of the evacuation design effect constructed in this research tests the safety performance of the selection and layout design of the equipment and facilities in metro stations after considering DFS pre-control measures from the two aspects of evacuation efficiency and evacuation risk. Among them, this research selected the traffic capability of an individual piece of equipment or facility and the emergency evacuation time under the overall design scheme as the evaluation indicators of the evacuation efficiency, and it selected the congestion possibility of each walking facility under the overall design scheme as the assessment indicators for the evacuation risk. The evacuation risk in the design scheme is manifested by computing the multifacility queuing network model of the metro station and screening the evacuation bottlenecks in the design scheme.

3.3 Development method of a BIM-based SEDT

The lack of availability of DFS tools is one of the greatest obstacles to the implementation of the DFS concept in construction engineering [37]. The BIM platform is increasingly used in the metro design industry due to the advantages it offers for visualization and data integration [66]. Based on the commonly used BIM platform Autodesk Revit, in this research, textual, numerical and computational DFS pre-control measures for the selection and layout design of equipment and facilities in metro stations are integrated into Revit. A SEDT specifically for designers was developed. The SEDT runs as a plug-in to Revit software, making it easy for designers to directly call DFS pre-control measures in Revit. To improve the design efficiency of designers in applying the SEDT, the development of the SEDT will be based on the division of the entire design phase of the metro station and the decomposition of the design content. Using the centralized development platform Visual Studio, five modules are developed, namely, the input module, storage module, query module, computational module, and bottleneck module. The development of the

SEDT serves designers in the safety design throughout the design stage: (1) in the preliminary design stage, the input module helps designers use the off-the-shelf metro-station-specific family library for rapid modeling. (2) In the basic design stage, the automation application of the DFS pre-control measures is implemented, in which the storage module implements the association between the BIM model and the DFS database and helps the designer to obtain various DFS pre-control measures for an individual piece of equipment or facility; the query module implements the automated inspection of the numerical DFS pre-control measures to help designers to check the numerical parameters. (3) In the detailed design stage, the automatic evaluation of the evacuation design effect is realized, where the computational module realizes the automatic verification of the computational DFS pre-control measures and helps the designer calculate the evacuation efficiency indicators and the bottleneck module helps the designer calculate the evacuation risk indicators of the overall design scheme and screen the evacuation bottlenecks. The corresponding relationship between each module and the design stage and the design content is shown in Fig. 9.

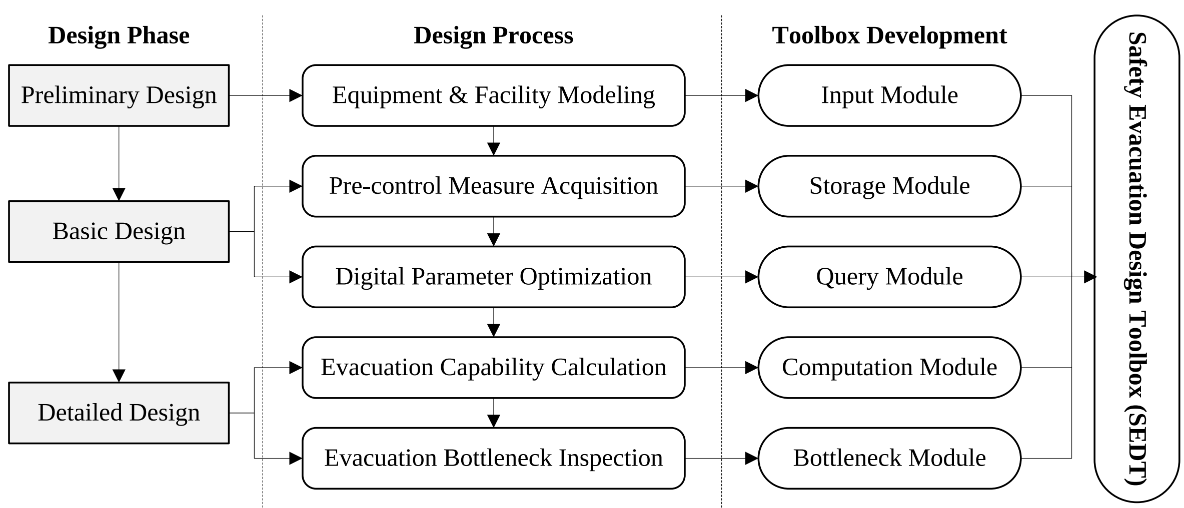

Fig. 9. Development of SEDT-oriented design phase and process.

3.3.1 Module 1: Input module

Due to the complexity of the metro station system and the wide variety of equipment and facilities used in such stations, to quickly construct a BIM model of a metro station, it is necessary to establish a family library of the equipment and facilities that are suitable for the design of the station. This library should include entrances, exits, passageways, escalators, and automatic ticket gates. To read the equipment and facility data in the BIM model of the metro station, the input module in the SEDT adopts the Revit secondary development technique, i.e., the Revit API connection method, to realize the loading and data extraction of the various equipment and facilities in the model. The input module provides a loadable and modifiable library of equipment and facilities that can effectively increase the efficiency in the preliminary design stage.

3.3.2 Module 2: Storage module

The storage module in the SEDT is developed to first store the DFS pre-control measures in the form of a database. Then, the DFS pre-control measures of the selected components can be displayed in a pop-up window via the integration of the BIM platform and DFS database. The functional implementation of this module is divided into two main parts. (1) The DFS database is built using Microsoft Access software and consists of a storage data table and a relational data table. The storage data table includes a Revit family table, an evacuation equipment and facility table, a design content table, a code table, a case table, and a document table; the relational data table includes a relationship table between the Revit family and equipment facilities and a relationship table between the evacuation equipment facilities and design content; the specific data organization relationships are shown in Fig. 10. (2) Using the integrated development environment software Visual Studio (VS), the components in the BIM model are linked with the storage data of each facility in Access through the connection between VS and Revit and that between VS and Access to realize the corresponding one-to-one mapping relationships between the model components and DFS pre-control measures. The storage module enables the designer to obtain all DFS pre-control measures corresponding to the BIM components through an information query; this can effectively guarantee the design norms in the basic design stage.

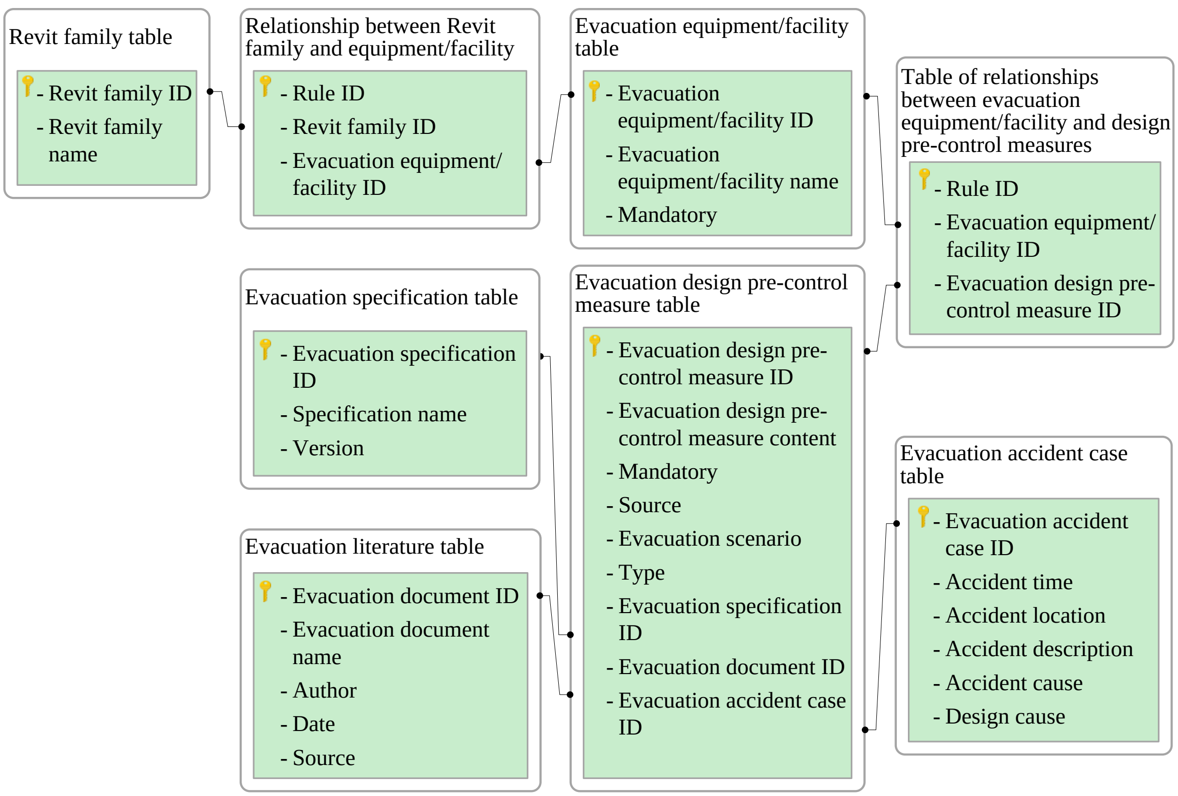

Fig. 10. Data organization relationships in the storage module.

3.3.3 Module 3: Query module

The query module is a further development of numerical DFS pre-control measures. When the designer uses this module to begin the layout design by querying the required equipment and the facility name, the numerical values of the design elements of the corresponding equipment and facilities assembled by the BIM model can be compared with those in the numerical DFS pre-control measures; the module then automatically verifies that the design meets the requirements. The functional implementation of this module is divided into two main parts as follows. (1) Microsoft Access software is used to extract the numerical DFS pre-control measures in the design content table, a database of numerical DFS pre-control measures based on the original DFS database is built, and a query class design element table, a query class rule table, and a query class design content table are added; the specific data organization relationships are shown in Fig. 11. (2) The Revit API is first used to read the values of the evacuation design elements in the BIM model (such as the number, size, and separation distance of the components); the numerical requirements in the design contents are then read, and finally, the two sets of values are compared to automatically determine whether the equipment and facility layout meets the numerical DFS pre-control measure requirements. The query module automatically displays numerical information such as parameters, quantities, and distances in accordance with the codes when performing the equipment and facility layout; this can effectively guarantee the accuracy of the design of the equipment and facility parameters in the basic design stage.

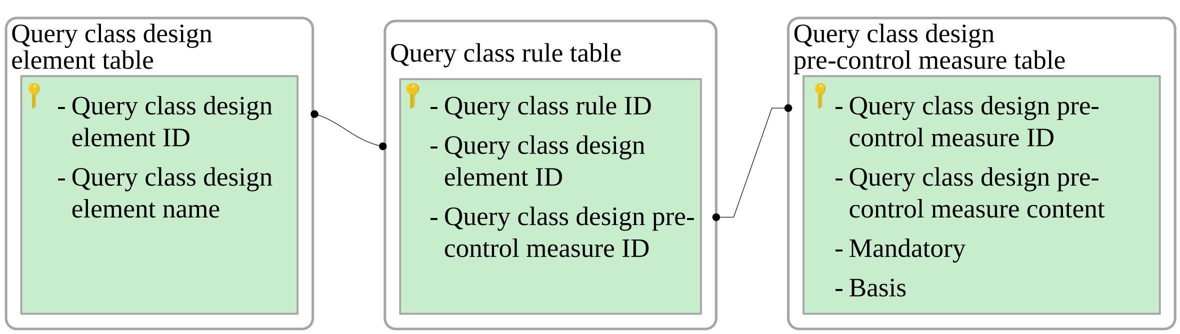

Fig. 11. Data organization relationships in the query module.

3.3.4 Module 4: Computation module

The computation module is a further development of the computational DFS pre-control measures for evacuation efficiency evaluation. The computation results are obtained by calculating the data read in the BIM model and the data entered in the user interface into the corresponding codes, and the corresponding results are obtained. The calculation of the evacuation efficiency includes checking whether the pedestrian emergency evacuation time under the overall equipment selection and layout design meets the mandatory fire protection rules in metro stations and whether the various walking facilities, fence gates, ticket gates, and entrances and exits have the capacity to satisfy passenger flows during the rush hour in line with the statistical law of local metro stations' operation situation. In view of the evacuation efficiency of the equipment and facilities directly determining the emergency capability of the metro station in responding to various emergencies, the Chinese code for the design of metros, the American standard for fixed guide way transit and passenger rail systems, the Japanese detailed code of fire prevention in the subway, and other design standards in various countries all take the evacuation efficiency index to meet the formulas and thresholds as mandatory requirements for the pre-control of the evacuation risks [23].

The functional implementation of this module is divided into two main parts. (1) The numbers of equipment and facilities are obtained using the Filtered Element Collector in the Revit API, and the geometric parameters of the equipment and facilities are obtained using the function "get_Geometry (Options opt)". (2) The formula function in the computational pre-control measures is constructed on the VS. The VS completes the computation by reading the parameters derived from the BIM model and the user interface and feeding the computation results to the BIM model in real time. The computation formulas and the parameters involved in the computation module are based on the *Code for design of metro* [52], as shown in Table 4. The calculation formulas and thresholds illustrated in Table 4 are mandatory DFS pre-control measures in the Chinese code for design. Therefore, when designers in other countries utilize the calculation module in the SEDT, they need to first identify all computational pre-control measures involved in the local design specifications and standards according to the DFS pre-control measure identification method proposed in Section 3.1. It is also necessary to modify the corresponding computation formula in the computation module so that designers can actively determine whether the evacuation efficiency meets the emergency evacuation requirements after completing the layout design. The computation module can evaluate the passenger evacuation time and the traffic capacity of each facility under the existing layout of equipment and facilities and effectively ensure that the overall design scheme in the detailed design stage conforms to all relevant evacuation formulas.

Table 4. Computational parameters and formulas used in the computation module.

Source	Parameter name	Parameter description	Unit
Revit	N_1	Number of ascending escalators	unit
	N_2	Number of descending escalators	unit
	N	Number of escalators	unit
	B	Total width of the escape stairways	m
	N_3	Number of automatic ticket gates	unit
	N_4	Sum of the net widths of the fence evacuation gates	m
	E	Total entrance and exit effective width	m
	A_1	Traffic capacity of a single escalator	persons/min*m
	A_2	Traffic capacity of escape stairways	persons/min*m
	A_3	Traffic capacity when each automatic ticket gate is opened	persons/min*unit
	A_4	Traffic capacity of the fence evacuation gate	persons/min*m
	C	Traffic capacity of the passageway	persons/min*m
User interface	Q_1	Maximum passenger section flow for one train in long-term or passenger flow control period super-peak hour	persons

Q_2	Maximum number of waiting passengers in long-term or passenger flow control period super-peak hour	persons
Q_3	Long-term peak hour outbound passenger flow	persons/min
Q_4	Long-term peak hour inbound passenger flow	persons/min
Q_5	Design passenger flow	persons/min
β	Direction nonequilibrium factor of passenger flow	/

Computation content	Computation formula
Time required for all passengers to be evacuated to the public area of the station hall or other safe areas	$T = 1 + \frac{(Q_1 + Q_2)}{0.9[A_1(N-1) + A_2B]} \leq 6$
Traffic capacity of escalator	$A_1N_1 + A_2B > Q_3$ $A_1N_2 + A_2B > Q_4$
Traffic capacity of automatic ticket gate and evacuation gate	$A_3N_3 + A_4N_4 \geq 0.9[A_1(N-1) + A_2B]$
Width and quantity of entrances and exits	$EC > \beta Q_5$

3.3.5 Module 5: Bottleneck module

The bottleneck module is developed for the identification of the evacuation bottlenecks by calculating the evacuation risk indicator of the overall design scheme, namely, the congestion probability for each walking facility. The decision model of the bottleneck module plug-in adopts the metro station multifacility queuing network model constructed in Section 5 of this research. To realize the automatic identification of the evacuation bottlenecks in the design scheme, the following two development steps must be completed. (1) The C# language is used to program the computation process of the bottleneck indicator of Section 5 and is packaged into a function call to generate a dll (dynamic linkable library) file. The main functions in the dll file and the function introductions are shown in Table 5. (2) The Revit API is first used to read the width (w) and length (l) of each type of walking facility in the BIM model; the function in the queuing dll file is then called according to the λ value (the pedestrian arrival rate at the entrance of the walking facility) entered in the user interface, and the computation is performed; finally, the congestion probability of the walking facility is returned to the display box of the Revit bottleneck module. The bottleneck module helps the designer find evacuation bottlenecks in the overall design scheme during the detailed design stage so that the walking facilities' evacuation risks can be optimized.

Table 5. Main functions of the dll file in the bottleneck module.

No.	Function name	Functionality
1	getTheta(double lambda, double pc)	Calculating the output rate θ of the walking facility based on the arrival rate λ and the congestion rate p_c of the walking facility
2	getEt(double en, double theta)	Calculating the time expected for passengers $E(T)$ of the facility based on $E(N)$ and θ of the walking facility
3	getMPn(long n, double ml, double mw, long c, double lambdaj)	Calculating the p_n of the stairways and escalators based on their width *mw*, length *ml*, maximum capacity *c*, arrival rate λ_j and quantity *n*
4	getMPc(double ml, double mw, long c, double lambdaj)	Calculating the congestion rate p_c of the stairways and escalators based on their width *mw*, length *ml*, maximum capacity *c*, and arrival rate λ_j
5	getMEn(double ml, double mw, long c, double lambdaj)	Calculating the $E(N)$ of the stairways and escalators based on their width *mw*, length *ml*, maximum capacity *c*, and arrival rate λ_j
6	getKPn(long n, double kl, double kw, long c, double lambdap)	Calculating the p_n of the passageways based on their length *kl*, width *kw*, maximum capacity *c*, arrival rate λ_p and quantity *n*
7	getKPc(double kl, double kw, long c, double lambdap)	Calculating the congestion rate p_c of the passageways based on their width *kw*, length *kl*, maximum capacity *c*, and arrival rate λ_p
8	getKEn(double kl, double kw, long c, double lambdap)	Calculating the $E(N)$ of the passageways based on their width *kw*, length *kl*, maximum capacity *c*, and arrival rate λ_p
9	result(string json)	Generating the desired results based on the json formatted information; returns the json format

Considering that if there is an emergency at metro stations, the most common emergency evacuation route is "platform → stairways and escalator → station hall → passageway and entrance/exit" [67], in the dll file, the specific steps of the internal algorithms of the result (string json) function are:

(1) *Step 1*: Acquire geometric information on stairways, escalators and passageways.

Parse information on stairways, escalators and passageways in json format.

(2) *Step 2:* Suppose that during an emergency evacuation, the pedestrian inputs of n stairways and escalators all come from the pedestrian output on the platform, and the corresponding pedestrian input value for each stairway and escalator is linearly related to the width of the stairway or escalator; then, the pedestrian output rate λ_j of each stairway and escalator can be calculated. The specific calculation process is as follows:

① Calculate the total width of the stairways and escalators (*mws*).

② With the pedestrian input rate (λ), the total width of stairways and escalators (*mws*) and the width of each stairway and escalator (*mwj*), calculate λ_j of each stairway and escalator.

Pseudocode programming is as follows:

```
mws=mw1+mw2+mw3+……+mwn
for(j=1;j<=n;j++)
{
lambdaj=lambda*mwj/mws;
}
```

(3) *Step 3:* According to the computational formula of bottleneck indicators for walking facilities proposed in Section 5, along with the callable functions in the dll file, the queuing theory index of each stairway and escalator can be calculated. The specific calculation process is as follows:

① Call function "getMEn(double ml, double mw, long c, double lambdaj)", calculating the congestion rate p_{cj} of each stairway and escalator.

② Call function "getMEn(double ml, double mw, long c, double lambdaj)", calculating the expected number of passengers $E_j(n)$ of each stairway and escalator.

③ Call function "getTheta(double lambda, double pc)", calculating the number of people output per second θ_j of each stairway and escalator.

④ Call function "getEt(double en, double theta)", calculating the service time expected by the passengers $E_j(T)$ of each stairway and escalator.

(4) *Step 4:* Suppose that during emergency evacuation, the pedestrian input of *p* passageways entirely comes from the pedestrian output of *n* stairways and escalators, and the corresponding pedestrian input value for a passageway is linearly related to the width of the passageway; then, the pedestrian input rate λ_p of each passageway can be calculated. The specific calculation process is as follows:

① Calculate the total width of the passageways (*kws*).

② Calculate the total pedestrian output rates of the passageways (θs).

③ With the number of people output per second θ_j of each stairway and escalator from Step 3, the total width of the passageways (*kws*), and the total pedestrian output rates of the passageways (θs), calculate the pedestrian input rate λ_p of each passageway.

Pseudocode programming is as follows:

kws=kw1+kw2+kw3+……+kwp

theta=theta1+lambda2+……+thetan

```
for(i=1;i<=p;i++)
{
lambdap=theta*kwi/kws;
}
```

(5) *Step 5:* According to the computational formula of the bottleneck indicators for walking facilities proposed in Section 5, along with the callable functions in the dll file, the queuing theory index of each passageway can be calculated. The specific calculation process is as follows:

① Call function “getKPc(double kl, double kw, long c, double lambdap)”, calculating the congestion rate of each passageway.

② Call function “getKEn(double kl, double kw, long c, double lambdap)”, calculating the expected number of passengers of each passageway.

③ Call function “getTheta(double lambda, double pc)”, calculating the number of people output of each passageway.

④ Call function “getEt(double en, double theta)”, calculating the service time expected by the passengers of each passageway.

(6) *Step 6:* Output result

Output the queuing theory index, the maximum congestion rate, and the corresponding number of each type of equipment and facility.

4 Case demonstration

Based on the DFS concept, this research constructs the identification method of DFS pre-control measures and evaluates the evacuation design effect for the selection and layout design of equipment and facilities in metro stations. Through the secondary development of Revit software, the SEDT is constructed to realize rapid modeling, input inspection and design effect evaluation, which helps designers in the selection and layout design of equipment and facilities for emergency evacuation safety and realizes the automation of the DFS application method. To verify the applicability and operability of the SEDT in the entire design phase, the metro station X in China was selected as a case. Specifically, the specific design tasks at specific design stages are presented to demonstrate the application of the five modules of the SEDT and to provide a basis for suggestions and improvements in the design of the metro station X.

4.1 Layout of the metro station

The metro station X is a two-story elevated island station in which the first underground floor of the main body is the Station Hall Level and the second underground floor is the Platform Level. This station is a nontransit station with a main building area of approximately 12,000 m^2. The geometric dimensions of the main walking facilities of the metro station X are reported in Table 6.

Table 6. Geometric dimensions of the main walking facilities.

Name	Location	Length	Width	Height
Platform Level	The second underground floor of the main body	144.0 m	24.0 m	7.0 m
Station Hall Level	The first underground floor of the main body	144.0 m	8.2 m	7.53 m
Stairway 1	Northwest corner, close to the management office	15.06 m	2 m	7.53 m
Stairway 2	Southwest corner, close to the management office	15.06 m	2 m	7.53 m
Stairway 3	North central, near Gate unit 1	15.06 m	2 m	7.53 m
Stairway 4	Central south corner, near Gate unit 2	15.06 m	2 m	7.53 m
Escalator 1	Northwest corner, near Stairway 1	12.80 m	1.2 m	7.53 m

Escalator 2	Southwest corner, near Stairway 2	12.80 m	1.2 m	7.53 m
Escalator 3	Central north corner, near Stairway 3	12.80 m	1.2 m	7.53 m
Escalator 4	Central south corner, near Stairway 4	12.80 m	1.2 m	7.53 m
Passageway 1	North central	22.30 m	4.20 m	/
Passageway 2	South central	25.60 m	7.00 m	/
Gate unit 1	Northwest corner	3.41 m	1.8 m	1.05 m
Gate unit 2	Southwest corner	4.37 m	1.8 m	1.05 m
Gate unit 3	Northeast corner	4.37 m	1.8 m	1.05 m
Gate unit 4	Southeast corner	3.41 m	1.8 m	1.05 m
Fence gate 1	Close to Gate unit 1	/	2.11 m	1.1 m
Fence gate 2	Close to Gate unit 4	/	2.30 m	1.1 m

Note: The lengths of the stairways and escalators refer to the projected lengths.

4.2 Application of the SEDT to the metro station

The SEDT creates five custom external buttons in the add-on module of the Revit software that are used to implement the input, storage, query, computation, and bottleneck checking functions. The specific interface of the SEDT in the Revit software is shown in Fig. 12. Through the five module plug-ins of the SEDT, the selection and layout design of the equipment and facilities in metro stations for emergency evacuation safety can be designed and optimized. The specific application process including five steps is described below.

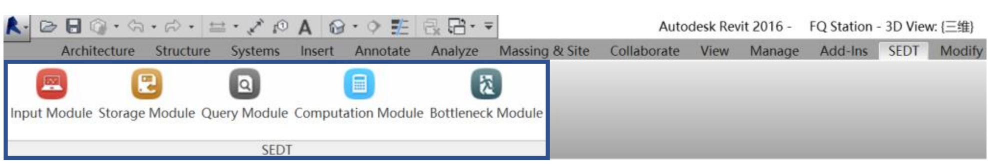

Fig. 12. SEDT interface.

4.2.1 Step 1: Use of the input module to realize the rapid modeling of a metro station

When building a BIM model for a metro station in the preliminary design stage, designers need a family of custom equipment and facilities in addition to the system families that the Revit software provides. These should include walls, gates, windows, floors, and stairways. To improve the modeling efficiency, the SEDT input module provides a common library of equipment and facilities in metro stations, as shown in Fig. 13. In the input module, the “Load Project” button under the Loadable Family Thumbnail is clicked to load the .rfa file of the corresponding family. By using the input module, the parameters of the required family files were adjusted according to Table 6, and the final BIM model and rendering sketch are shown in Fig. 14.

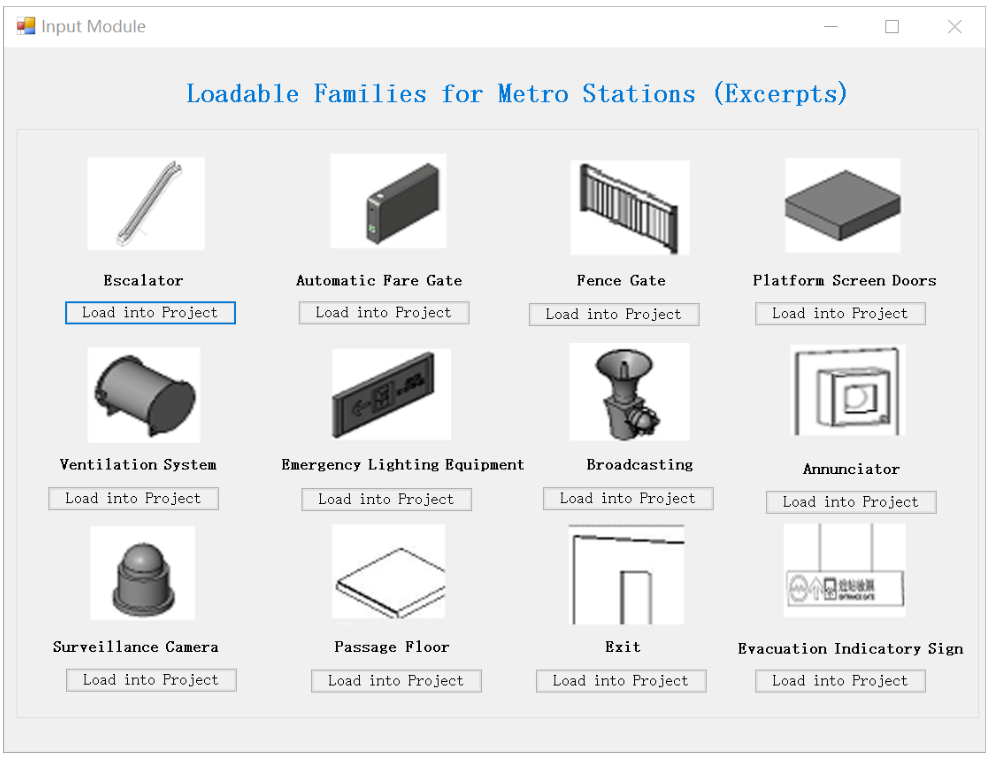

Fig. 13. SEDT input module interface.

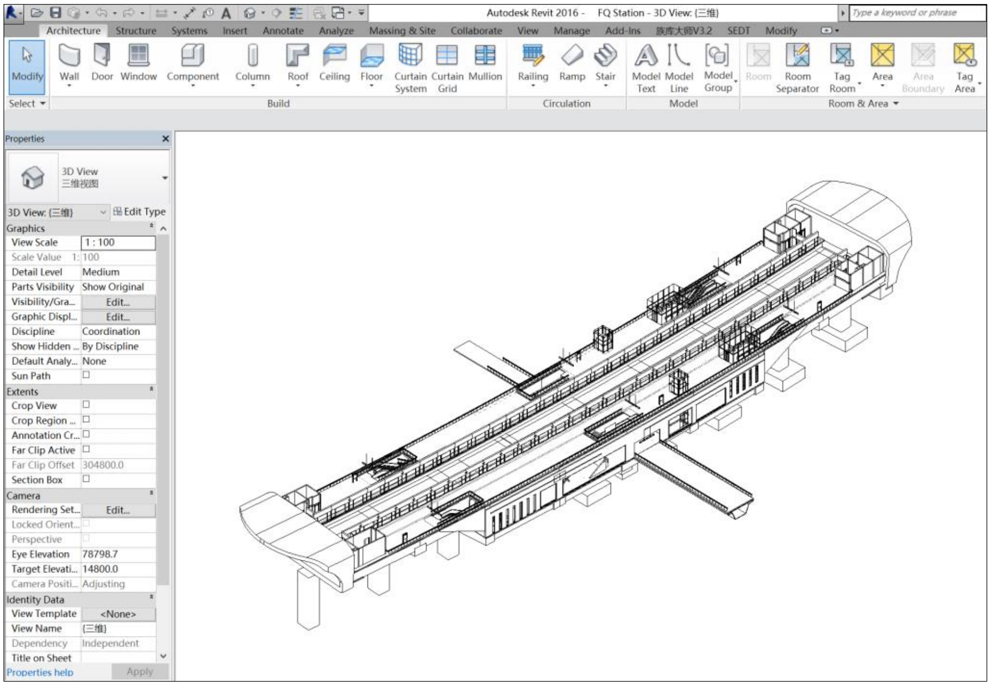

Fig. 14. BIM model of the metro station X.

4.2.2 Step 2: Use of the storage module for the automatic display of DFS pre-control measures

Designers usually decide the selection and layout design of the equipment and facilities in metro stations based on their own design experience and on the design codes. Thus, designers often forget to consider fragmented DFS pre-control measures scattered across massive design specifications and lack updated knowledge regarding the latest DFS pre-control measures. The storage modules of the SEDT ensure that designers are aware of all DFS pre-control measures when arranging the individual equipment and facilities. Taking the emergency lighting facilities of the metro station X as an example, after the designer selects the family of emergency lighting facilities and clicks the icon of the storage module in the BIM model, the BIM model automatically queries information such as the design contents, mandatory requirements, and sources that the component needs to meet. The interface of the storage module is shown in Fig. 15. Designers can use the DFS pre-control measures provided by the storage module to determine whether the existing configuration and layout of the equipment and facilities meet the mandatory requirements or whether there is a need to modify or optimize the layout. Because the storage module has an open source of information, developers can enrich the database by adding related codes, cases, and other information to provide designers with systematic, scientific, and up-to-date safety design guidance.

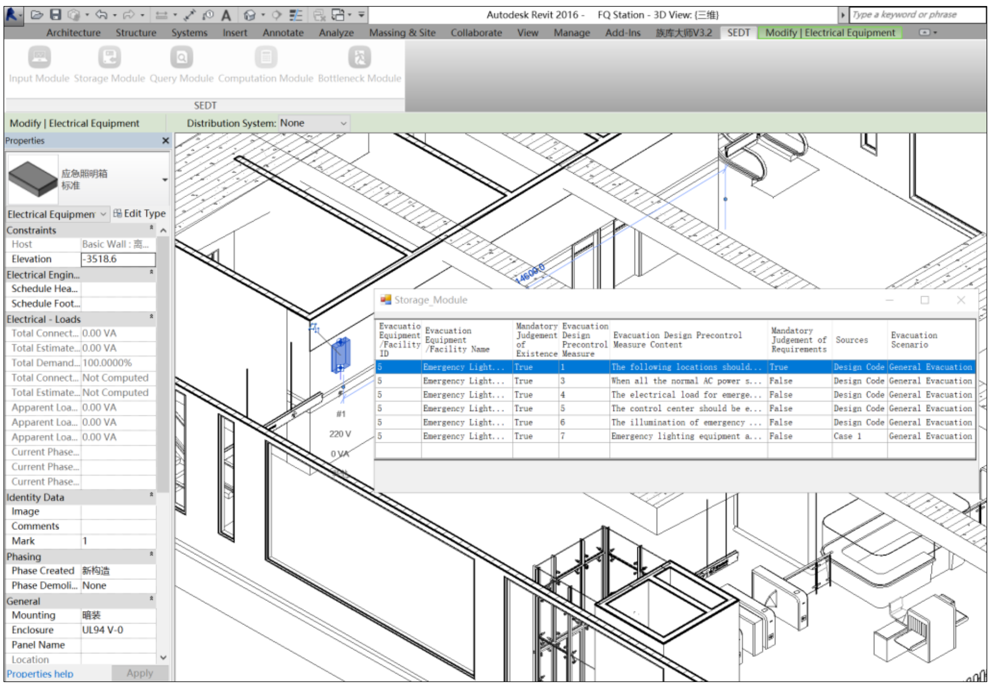

Fig. 15. Interface of the storage module.

4.2.3 Step 3: Use of the query module for the automatic verification of numerical DFS pre-control measures

Compared with the storage module, the query module of the SEDT can automatically check the numerical DFS pre-control measures during the basic design stage, which assists designers in completing the parametric setting of the layout of the individual pieces of equipment and facilities. When the designer clicks the “Query Module” button in the SEDT panel, the initialization interface is loaded. The user can select the evacuation design element ID that needs to be automatically checked according to the evacuation design element table on the right side of the interface and query whether the information in the model satisfies the requirements for the numerical DFS pre-control measures. For example, in cases involving the number of entrances and exits with ID=1 and the width of passageways with ID=2, the corresponding numerical DFS pre-control measures are displayed on the interface after the query module plug-in is run. Running the results shows that both the number of entrances and exits and the width of the passageways in the BIM model meet the requirements, as shown in Figs. 16 and 17.

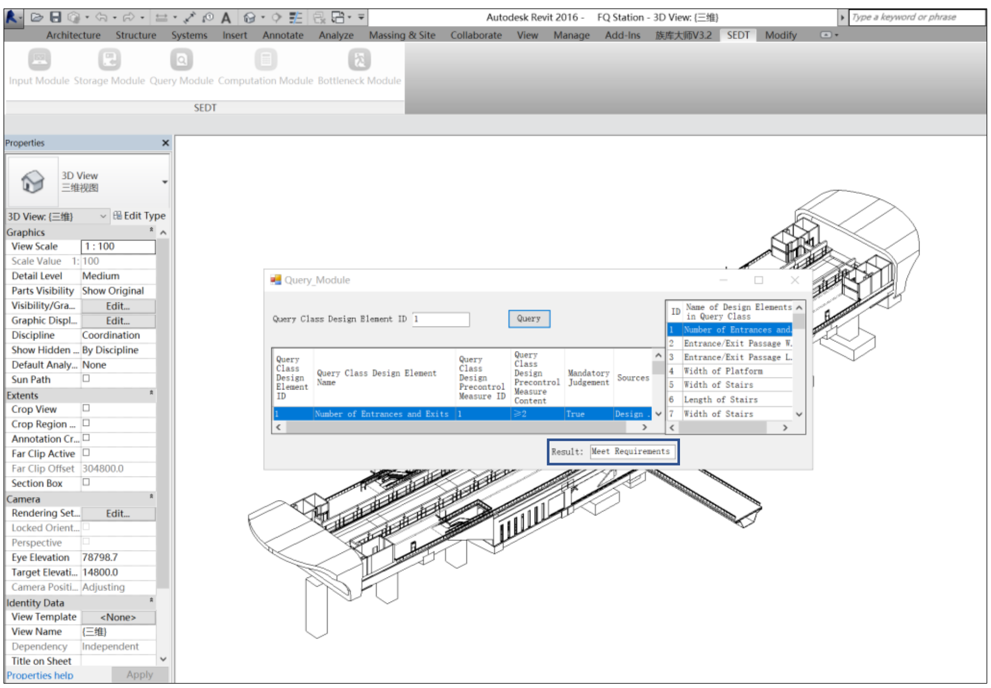

Fig. 16. Computational result of query ID=1.

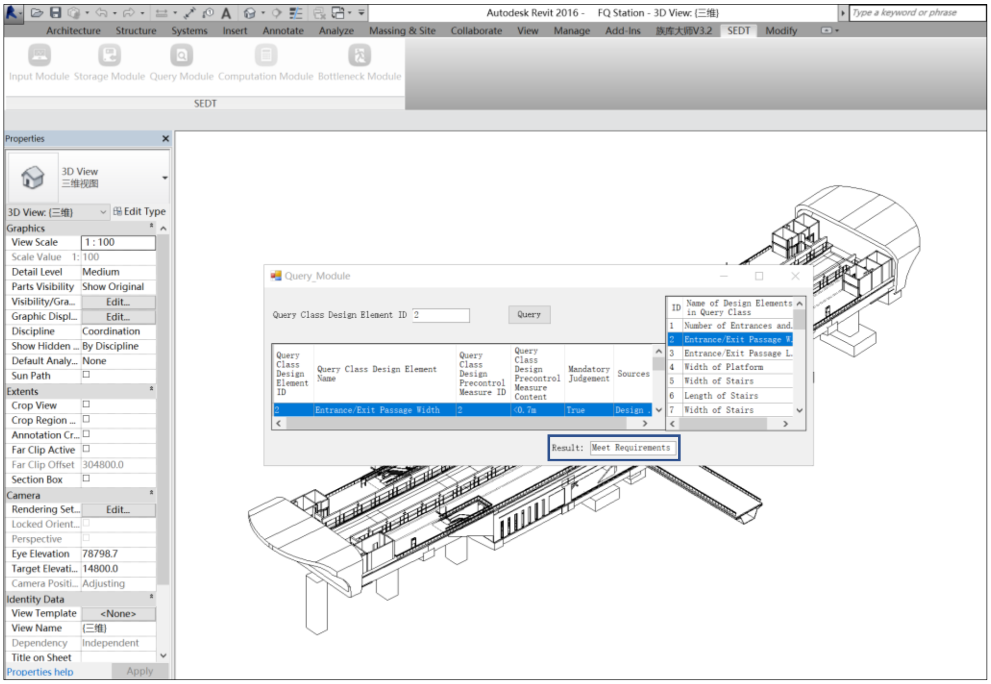

Fig. 17. Computational result of query ID=2.

4.2.4 Step 4: Use of the computation module to realize the automatic computation of the evacuation efficiency

After completing the overall selection and layout design of the equipment and facilities, the designer can use the SEDT computation module during the detailed design stage to automatically evaluate the current metro station evacuation efficiency, namely, the individual traffic capacity of each facility. According to the evaluation results, the names of the equipment and facilities that do not meet the required evacuation efficiency are fed back to the designers. Since the passenger flow of the metro station should be determined by the passenger flow plan that exists prior to the evacuation design, the passenger flow of the metro station is a known value. The maximum passenger cross-sectional flow (Q1) of one inbound train at the metro station X during the long-term or passenger flow control period super-peak hour is 1,000 persons, and the maximum number of waiting passengers (Q2) on the platform during the long-term or passenger flow control period peak hour is 800. The results of running the computation module are shown in Fig. 18. The results show that according to the computation rules of the metro design codes, the passenger evacuation time of the metro station is 3.47 min, a value that meets the Chinese standard evacuation time requirement. Checking the traffic capacity of the facility, however, shows that the evacuation abilities of the fence gate and the ticket gate do not meet the requirements.

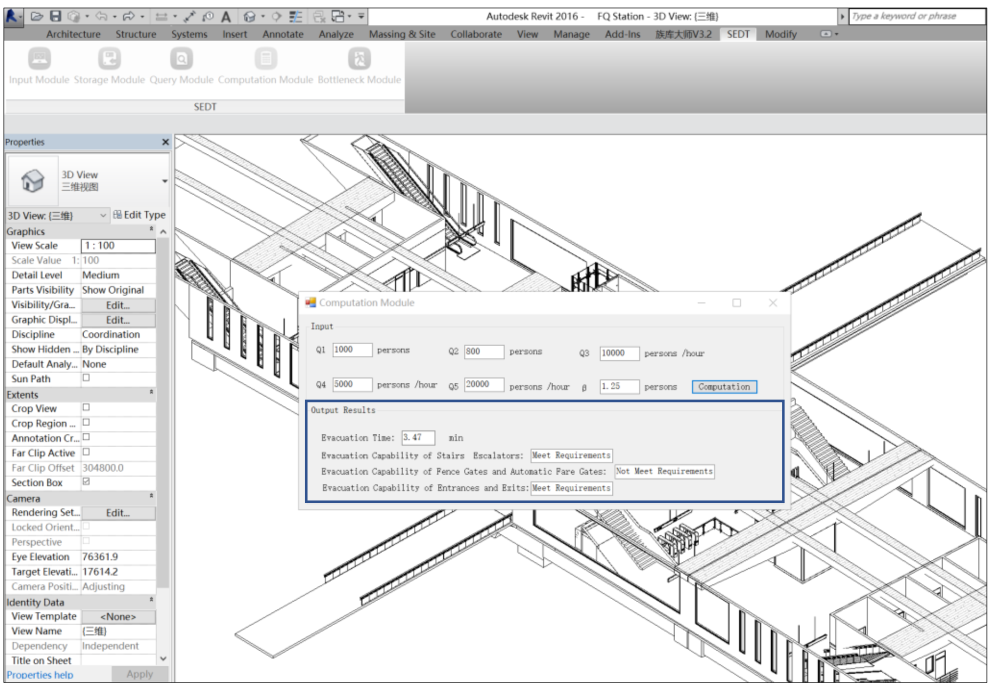

Fig. 18. Computational results obtained using the computation module.

Notes: (1) input parameter: Q1=1000, Q2=800, Q3=10000, Q4=5000, Q5=20000, β=1.25;

(2) output parameter: T=3.47min.

4.2.5 Step 5: Use of the bottleneck module to realize the automatic screening of evacuation bottlenecks

Designers can use the bottleneck module of the SEDT in the detailed design stage to automatically screen the evacuation bottlenecks in the design scheme and automatically display the location information and the probability of congestion. When developing an emergency evacuation plan for the metro station X, by assuming that the flow speed of the platform is 12 persons/s, the designer can automatically acquire the probability of congestion in each stairway, escalator, and passageway in the design scheme by clicking the button of the "Bottleneck Module"; when this is done, the IDs of the parts of the walking facilities that are most likely to become congested are displayed. The display interface of the results of this operation is shown in Fig. 19. The designer can query the names of the equipment and facilities corresponding to each ElementID according to the ElementID displayed on the interface. The operation results of the bottleneck module show that the design of the metro station X satisfies the relevant requirements for evacuation design in the Chinese codes but that the probability of congestion (p_c) of each stair and escalator exceeds 0.1. Escalators 1, 2, 3, and 4 have the most urgent need for improvement; the p_c of these escalators reaches 0.138.

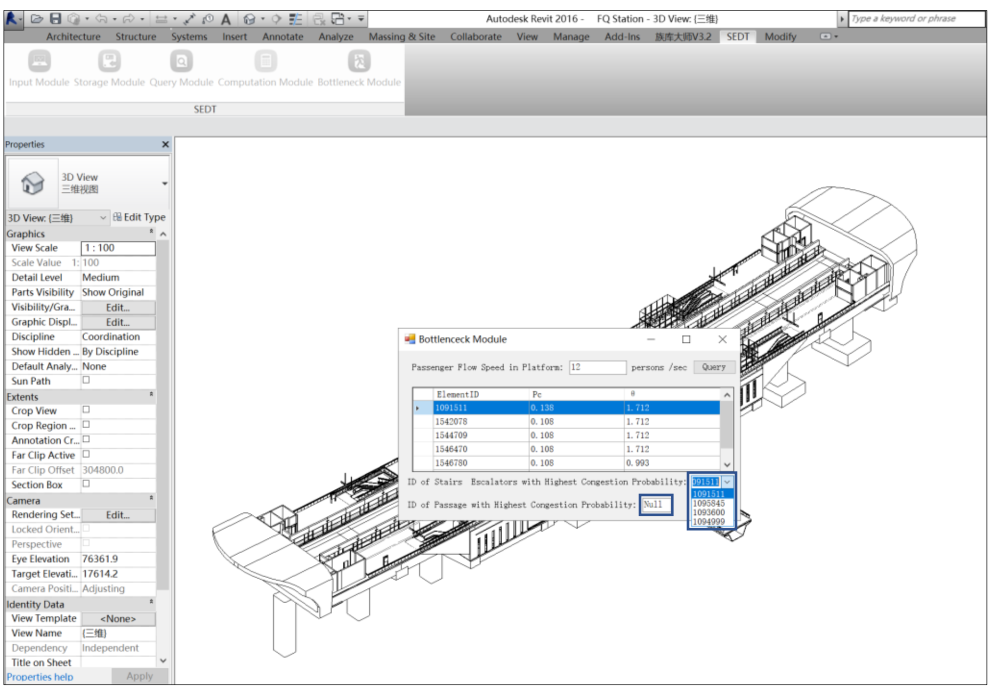

Fig. 19. Bottleneck module operation results.

4.3 Design optimization strategy based on the SEDT operation results

According to the operation results of the storage module, the query module, the computation module, and the bottleneck module of the SEDT, designers can formulate corresponding optimization strategies for the selection and layout design of the equipment and facilities. When the interface of the query module shows that the selection or layout of the equipment and facilities do not meet the numerical DFS pre-control measures, designers can refer to the values displayed in the query module to adjust the parameters of the current equipment and facilities to meet the requirements. When the interface of the computation module shows that equipment and facilities do not meet the computational DFS pre-control measures or when the interface of the bottleneck module shows an evacuation bottleneck with a high congestion probability, designers can optimize them according to the DFS pre-control measures of the corresponding equipment and facilities in the storage module. After the design optimization is completed, clicking the calculation module and the bottleneck module again would be helpful for determining whether the layout design can meet the requirements of all evacuation efficiency indicators and evacuation risk indicators.

Based on the feedback of each module during the design process of the metro station X, the following optimization strategies are proposed:

(1) The designer can adjust the selection and set parameters of the equipment and facilities through the use of DFS pre-control measures in the storage module and the query module.

(2) According to the operation results of the computational module, the evacuation time in the evacuation efficiency indicators meets the requirements, but the evacuation capacities of the ticket gates and the fence gates do not meet the requirements. Based on DFS pre-control measures in the storage module

and the query module, there are two ways to optimize the design: the first is to reduce the traffic capacities of the escalators within a certain limit, and the second is to increase the traffic capacities of the ticket gates and the fence gates. By analyzing the existing layout design, it is found that the total evacuation time would be affected by reducing the traffic capacity of the stairways and escalators. In this way, increasing the number of the automatic ticket gates has a strong operability. Meanwhile, each gate unit in the existing layout design only embraces 3 automatic ticket gates. When the designer adjusts each gate unit to cover 5 automatic ticket gates, the traffic capacity of the ticket gates and the fence gates can be verified by the relevant formulas in Table 4. The interface of the computation module is shown in Fig. 20.

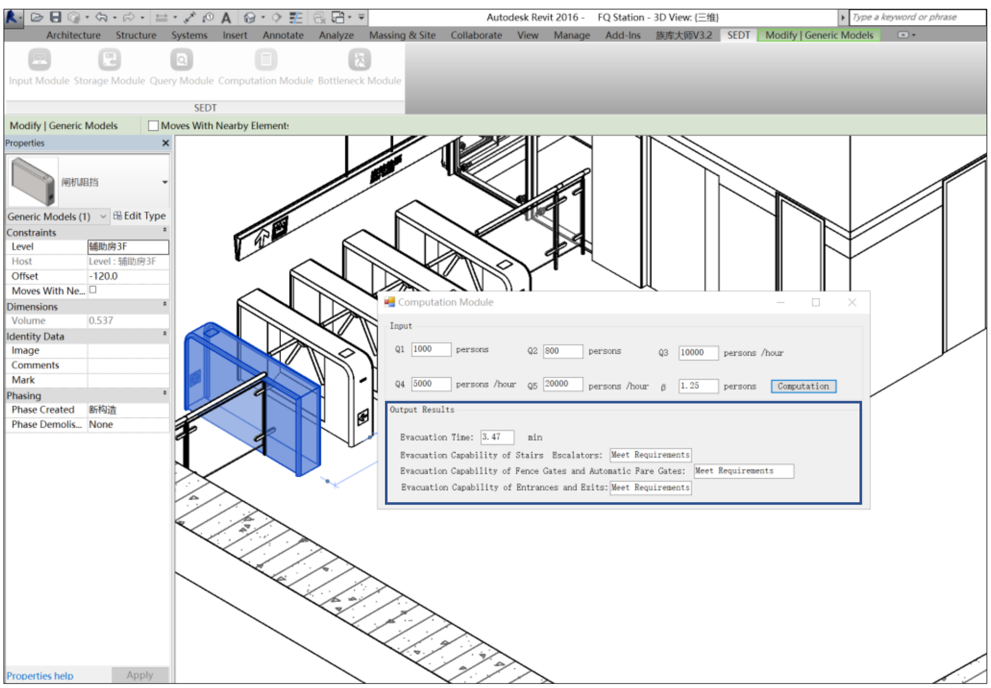

Fig. 20. Interface of the computation module after design optimization.

(3) According to the operation results of the bottleneck module, the evacuation bottlenecks in the existing design scheme are Escalators 1, 2, 3, and 4. Based on the DFS pre-control measures in the storage

module and the query module, designers can choose to increase the width or the number of escalators to reduce the probability of congestion. In light of the limitation of structure space, it is not possible to install an intact stairway next to the escalator. Therefore, after the designer modifies the width of the escalator to 1.6 meters, the congestion probability of the 4 escalators is deceased to 0.083 by computing the bottleneck module, which meets the DFS requirements. The interface of the bottleneck module is shown in Fig. 21.

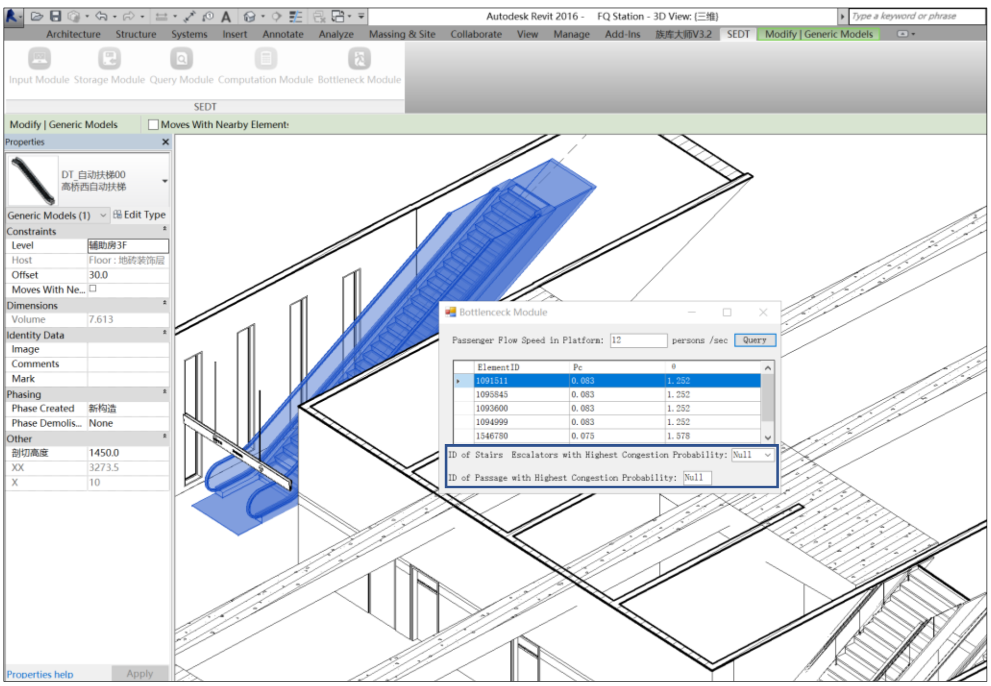

Fig. 21. Interface of the bottleneck module after design optimization.

5 Conclusions and future work

5.1 Theoretical contribution

With the surge in Chinese metro operations, metro design needs to consider emergency evacuation safety problems in metro stations. To realize the selection and layout design of the equipment and facilities in metro stations for emergency evacuation safety, this research proposes a DFS application method including the identification of DFS pre-control measures and the evaluation of the evacuation design effect based on the DFS concept.

Some studies have identified partial DFS pre-control measures relating to the equipment and facilities in metro stations, such as the layout and evacuation capacity of the equipment and facilities. However, there is no systematic summary or classification of the DFS pre-control measures for emergency evacuation. This research addressed this gap by proposing an identification method of DFS pre-control measures for emergency evacuation and establishing a DFS database including equipment facility names, design elements, design content, mandatory judgment, source of measures, and types of measures through the standardized retrieval, selection, identification and coding of pre-control measures. The method includes the standardized identification criteria and a classification system. The identification criteria facilitate the standardization update and maintenance of the open source DFS database. The classification system helps the DFS pre-control measures to be automatically compiled on the BIM platform.

The method for the evaluation of the evacuation design effect aims to objectively test the evacuation efficiency and evacuation risk of the metro station design scheme after considering the DFS pre-control measures. The traditional evaluation of the evacuation effect mainly focuses on the traffic capability of the equipment and facilities and the evacuation time of passengers that reflects the evacuation efficiency, however, there are few evaluation indicators of the evacuation risk based on the design scheme. This research addressed this gap by constructing a multifacility queuing network model for metro stations based on queuing theory, calculating the congestion probability of the walking facilities, and screening the evacuation bottlenecks of the design scheme. This approach helps designers to further optimize the walking facilities that have evacuation risks and provides a reference for developing an emergency plan, which can effectively avoid the inclusion of walking facilities with high congestion probability in the emergency evacuation route. Meanwhile, the existing simulation research on emergency evacuation is generally based on the established building models, which is by altering pedestrians' characteristic data (behavior, psychology, etc.) to calculate the evacuation efficiency of personnel in different emergency scenarios to make the optimal evacuation path to refine the emergency plan under different emergencies [68]. However, the dynamic optimized pre-proposal for an emergency cannot avoid the inherent defects of metro station designs. Therefore, a multifacility queuing network model is constructed in the study. By inputting the data, such as the pedestrian volume, density and walking speeds, in accordance with the statistical rules of the local metro stations, into the constructed multifacility queuing network model in this study, the evacuation bottleneck points in the layout design can be screened out. Subsequently, designers can easily adjust the parameters and layout of the equipment and facilities in the layout design until the evacuation bottleneck points are eliminated and the safety evacuation risk is minimized at the stage of design, to transform the passive safety management to the proactive prevention of active safety management.

5.2 Practical implications

To improve the application effect of the DFS concept, this research provides a SEDT for metro station designers with rapid modeling, input inspection and effect evaluation functions based on the BIM platform. The SEDT achieves the automation of the DFS application method by the secondary development technique of Revit. This research innovatively correlates the five functional plug-ins in the SEDT with the design processes, helping designers to clarify the safety design content that can be realized in each design stage and improving the application efficiency of the SEDT. The SEDT consists of five modules. In the preliminary design stage, the designer runs the input module and implements the rapid modeling of a metro station through the built-in metro station-specific loadable families. In the basic design stage, the designer runs the storage module and the query module to realize the automatic display and numerical verification of the DFS pre-control measures through the association of the built-in DFS database with the BIM model. In the detailed design stage, the designer runs the computation module and the bottleneck module, and then the effect of the evacuation design is automatically evaluated through the built-in computational DFS pre-control measures and the multifacility queuing network model. To verify that the SEDT can serve the safety design process throughout the entire design phase, the selection and layout design of the equipment and facilities in which emergency evacuation safety is considered is evaluated through a case of the metro station. Based on the SEDT operation results, strategies for optimizing the station design for improving the emergency evacuation safety are proposed.

The proposed BIM toolbox SEDT in this research has two application advantages. First, in terms of application scenarios, the SEDT focuses on the evacuation design of metro stations. It expands the functions of the existing toolbox, which is mainly applied to identify and control the safety risks in metro construction, ensuring the safety design concept running through the operation phase of metro stations. Second, in terms of application functions, the SEDT innovatively integrates various functions based on the layout design of metro stations, which includes the rapid modeling of equipment and facilities, the automatic acquisition and optimization on the pre-control measures of safety designs, the automatic calculation of the evacuation efficiency, and the automatic identification of the evacuation bottlenecks. It also makes the human-computer interaction interface clear and intuitive. Additionally, it also fills the gap in the existing toolbox, such as the non-correspondence between application functions and design workflows and the repeated switching between the BIM model and other evacuation decision software in the layout design. Therefore, the proposed SEDT would be suitable for the selection and layout design of equipment and facilities in all metro stations. Given that in the process of developing the storage module, query module and bottleneck module, this study adopts the safety evacuation pre-control measures identified in the Chinese code for design and historical accident cases happening in Chinese metro stations, it is necessary to update the pre-control measures and calculation parameters in the SEDT based on the proposed DFS pre-control measure identification process according to local design specifications when applying the SEDT in other countries. The standardized development process of each module of the SEDT is conducive to the worldwide promotion of safety design for the emergency evacuation of metro stations.

5.3 Limitations and future work

The developed methodology has certain limitations. In terms of the identification of the DFS pre-control measures, in this research, national codes, accident cases, and periodical literature are used as data sources. With the update and improvement of the codes, accident cases and research related to the emergency evacuation of metro stations, the DFS pre-control measures will be more comprehensive. In evaluating the evacuation risks, in this research, only stairways and passageways are used as examples to explain how to build a queuing theory model. In the future, other facilities such as automatic ticket gates, entrances and exits, and other walking and guiding facilities can also be introduced into the multifacility queuing network model to establish queuing rules. At the same time, the passenger flow characteristics of the metro station's location can be taken into consideration to correct the passenger flow parameters involved in the queuing theory model in real time, which can better meet practical design requirements and improve the accuracy of the evacuation bottleneck screening. For the development of the SEDT and to further improve the work efficiency of the designer, the ability of the SEDT to directly extract information in the BIM model can be enhanced. For the application scenario of the SEDT, to help global metro station designers to implement the concept of DFS, the geographic location of metro stations can be set in the input module. In the following design, the storage module can automatically invoke the DFS knowledge base containing different national codes for design and passenger flow plans, and the related values and formulas in the query module, computation module, and bottleneck module can also be replaced automatically. In this research, a feasible automation design scheme for reducing the risk associated with the emergency evacuation of metro projects during their operation is provided. Our future research will focus on the expansion of DFS pre-control measures and improvement of the toolbox operation performance, gradually promoting the process of the intelligent safe design of metro engineering.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

No, thanks.