sustainability

MDPI

Article

Simulation-Based Resilience Evaluation for Urban Rail Transit Transfer Stations

Xinyao Yin, Junhua Chen * and Yuexuan Li

School of Traffic and Transportation, Beijing Jiaotong University, No. 3 Shang Yuan Cun, Hai Dian District, Beijing 100044, China; 23120942@bjtu.edu.cn (X.Y.); 20221202@bjtu.edu.cn (Y.L.)
* Correspondence: cjh@bjtu.edu.cn; Tel.: +86-15287979071

Abstract: Disturbances often occur in transfer stations; however, little is known about the weaknesses of transfer stations and their ability to cope with passenger flows. Therefore, this paper introduces resilience into the study of transfer stations to enhance their emergency response processes and improve the sustainability of URT networks. It establishes a two-level fuzzy evaluation model, using the G1 weighting method, to assess resilience across various scenarios (daily operation, heavy passenger flow, and emergencies) and identify weaknesses; then, corresponding enhancement strategies are proposed. First, factor sets are established according to resilience stages, including rapidity before disturbance, robustness, redundancy, resourcefulness, and rapidity after disturbance. Using the G1 method, the weight matrix for each factor is calibrated, and a membership degree matrix is determined based on their affiliation with the review set. Multiplying the weight matrix and membership degree matrix yields the resilience value. We apply these steps to a representative station with the assistance of Anylogic simulation in calculating the hard-to-obtain data, yielding a peak-hour resilience value of 0.3425, which indicates a "poor" rating in the review set. By combining the peak-hour resilience with resilience curves under different multiples of peak-hour flows, an enhancement prioritization strategy is proposed for the station, which can act as a reference for the management of URT transfer stations.

Keywords: resilience; sustainability of urban rail transit; two-level fuzzy evaluation model; G1 weighting method; Anylogic simulation

check for updates

Citation: Yin, X.; Chen, J.; Li, Y. Simulation-Based Resilience Evaluation for Urban Rail Transit Transfer Stations. *Sustainability* **2024**, *16*, 3790. https://doi.org/10.3390/su16093790

Academic Editor: Marilisa Botte

Received: 12 March 2024
Revised: 26 April 2024
Accepted: 29 April 2024
Published: 30 April 2024

1. Introduction

Urban rail transit (URT) attracts a large number of passengers due to its punctuality and high efficiency. However, disturbances always happen in URT systems. Transfer stations, as important nodes in URT networks, experience highly concentrated passenger flows and complex passenger flow organizations. If a transfer station is disturbed, it will cause an adverse chain reaction on the line and the URT network; this may even amplify the initial disturbance and thus affect the orderly operation of the wider city.

When encountering a disturbance, a transfer station undergoes two processes, the disturbance-resistance process and the recovery process, and contains five states. With the reference resilience theory in [1], we plot these states in Figure 1. Before a disturbance, the system is in the initial stable stage. When a disturbance occurs at time t_d, the system enters a stage continuously influenced by the disturbance. During this stage, the system is initially in a degraded state, and its resilience drops sharply. When the resilience drops to a certain extent, the system begins to recover gradually after a steady-state period. Then, it enters a new stable stage, in which the system resilience may be higher than ($P(t_n) > P(t_i)$), lower than ($P(t_n) < P(t_i)$), or equal to ($P(t_n) = P(t_i)$) the initial resilience level, depending on the recovery ability of the system itself. The characteristics of these two processes determine the transfer station's resilience. However, to date, there is still no systematic transfer station resilience evaluation system. For the evaluation of transfer station resilience, the resilience evolution process, the characteristics of resilience during the evolution process, the components contained in these characteristics, and the comprehensive evaluation method are of great significance. These elements constitute the transfer station resilience comprehensive evaluation system discussed in this paper.

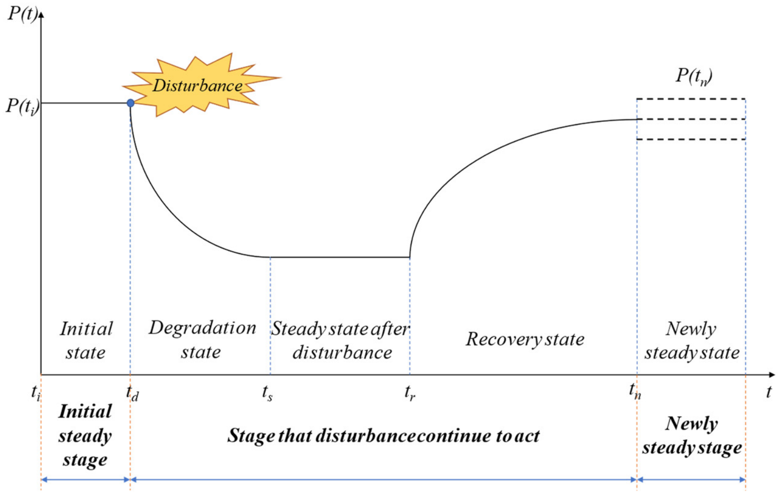


Figure 1. Resilience stages and five states.

Based on the existing resilience theory, this paper summarizes the resilience development stages of transfer stations and the resilience components contained in each stage. Subsequently, a model is constructed to quantitatively assess the ability of URT transfer stations to resist disturbances. Once this model is built, it is applied to a representative transfer station with the assistance of Anylogic simulation to evaluate its resilience. Based on the evaluation results, priority is given to measures that can be implemented to improve weak points when passenger flow reaches a certain level during daily operations, in order to enhance the resilience of the transfer station and the resistance of the URT network to damage. This has great practical significance for improving the service level of transfer stations and enhancing the sustainability of URT networks. While a quantitative evaluation system for transfer stations remains a gap in current research, the results of this research can guide the design of schemes for managing heavy passenger flows to cope with disturbances in various scenarios, such as train schedule adjustments and station flow-restriction measures. This serves as important support for optimizing rail traffic control and enhancing the sustainability of urban transportation.

The remainder of this paper is organized as follows: Section 2 provides a literature review on the current state of quantitative resilience research in rail transportation. Section 3 presents the proposed resilience assessment model and provides the calculations for each component in the model. In Section 4, a case study is presented to demonstrate the computational tractability of the model and to propose a recovery strategy based on the computational results. Section 5 concludes the paper, presents future research directions, and provides a thorough discussion of the results.

2. Literature Review

Holling, an ecologist, first conceptualized resilience and applied it to study an ecosystem. In 1973, Holling [2] distinguished the elasticity and stability measures, and put forward measurement methods. After introducing it into the ecosystem, Holling [3] defined resilience as engineering resilience in 1996. He used the time taken for the system to recover to its pre-disturbance state to describe the system's resilience. Since then, resilience has been introduced into psychology, power systems, water resources systems, urban systems, transportation systems, and other fields for extensive research. In 2006, Murray-Tuite et al. [4] clearly defined the resilience of transportation systems for the first time and suggested that it can be characterized according to four characteristics: adaptability, safety, mobility, and recovery. Cats and Jenelius [5] developed a dynamic and stochastic notion of public transport network vulnerability, which laid a foundation for the resilience research of various transportation networks. Then, in 2015, Mattsson and Jenelius [1] provided an overview of recent research on the vulnerability and resilience of transport systems. Amghar et al. [6] proposed a definition of RaaS (resilience as a service) dedicated to transportation systems to integrate the available resources of different service providers to maintain the system's resilience. The research in the above articles has advanced the development of a resilience measure for transportation and provides lessons on researching the resilience of railway systems.

Based on the resilience research of transportation systems, many scholars have conducted relevant research on the evaluation of railway network resilience. Lu et al. [7] demonstrated a resilience approach for rail transit networks under daily operational incidents. Li et al. [8] proposed a resilience evaluation method based on graph theory to quantitatively evaluate the performance and recovery speed of urban rail transit systems and evaluated the importance of each station in an urban rail transit network. With the development of more and more rail transit resilience research articles, Bešinović's [9] review paper set up a field-specific definition of resilience in railway transport and gave a comprehensive, up-to date review of railway quantitative resilience papers. Vigile Marie Fabella et al. [10] quantified the vulnerability of railroad infrastructure to natural disasters for sustainability purposes to measure resilience. Tang et al. [11], by extending the linear-programming optimization model, studied the resilience performance of an urban rail transit system. Watson et al. [12] extended state-of-the-art techniques for quantifying infrastructure resilience in the context of composite natural and man-made hazards and used a URT network as a proof-of-concept for infrastructure systems. Chen et al. [13] used the average loss ratio of time-related performance indicators to evaluate the resilience of urban rail transit networks and proposed a simulation-based resilience evaluation flow chart. Zhang [14] et al. put forward a resilience-based optimization model for choosing an optimal restoration sequence scheme. Zheng et al. [15] proposed a comprehensive resilience evaluation index for URT networks to ensure the sustainability of URT networks. Knoester et al. [16] presented a data-driven quantification approach for an ex post assessment of the resilience of railway networks. At present, many scholars have conducted research on the assessment and optimization of rail transit network resilience and proposed strategies for recovery after network disturbance, which greatly promotes the development of the theory of rail transit network anti-disturbance. However, very few studies have been implemented to address strategies for the internal recovery of individual nodes, which is actually a key aspect of recovery after network disturbance.

In recent years, some studies have introduced resilience into the study of URT stations. Jiao et al. [17] developed an assessment model for evaluating metro stations' resilience levels. Bešinović et al. [18] proposed an integrated disruption management model for integrating the disruption management of traffic, passengers, and stations on urban railway lines. Li et al. [19] proposed optimizing the resilience of urban rail systems by considering the influence of delayed trains and overcrowded passenger flows in the stations. At present, there are few studies on the resilience of URT stations, and most of the existing studies are based on a single disturbance scenario such as heavy rain or heavy passenger flow, and there is almost no assessment of station resilience under multiple scenarios. In particular, there is a gap in the research on the resilience of transfer stations. As a key node in a URT network, once the transfer station is disturbed, the whole line or even the whole URT network will be greatly affected. Therefore, the main research question in this study is as follows: how can we assess the disturbance–resistance ability of a transfer station under multiple disturbance scenarios and thus propose enhancement strategies?

To answer this research question and address the research gap, this paper introduces a resilience assessment study of transfer stations. This study aims to identify the weak points in transfer stations, determine the corresponding strategies to improve these weak points at different passenger flow levels, and thereby enhance the anti-disturbance and recovery capabilities of URT transfer stations. Additionally, it aims to improve network resilience and sustainability from a network perspective within the URT network.

3. Methodology

3.1. Establishment of Resilience Assessment Model for an Urban Rail Transit Transfer Station

This paper adopts a second-level fuzzy comprehensive evaluation model to quantitatively and comprehensively evaluate the resilience of the transfer station, using the G1 weighting method to obtain the weight of the factors. This comprehensive evaluation model generally has the steps shown in Figure 2.

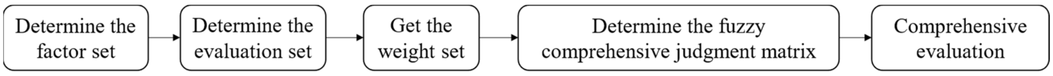


Figure 2. Flow chart of fuzzy comprehensive evaluation.

3.1.1. Determining the Evaluation Factor Sets

Some scholars [20] summarize the characteristics contained in the three stages of a resilience change as "4R characteristics", including **robustness**, **redundancy**, **resourcefulness**, and **rapidity**.

In this paper, **robustness** mainly refers to the ability of existing resources in the urban rail transit transfer station system to resist disturbance, which is a basic ability of the system and a key factor in the sustainability of the system. **Redundancy** mainly refers to the disaster-preparedness capacity and capacity surplus of transfer station facilities, which are related to the accommodation capacity of the station's equipment and facilities. This is the foundation for the sustainability of the system. **Resourcefulness** mainly refers to facilities and equipment that provide passengers with an option to complete evacuation during the disturbance–resistance stage. **Rapidity** not only indicates the speed of the response of the transfer station system to the disturbance after the disturbance occurs, but also indicates the speed at which passengers move within various facilities before the disturbance occurs. This contributes to sustainable quality development. The action process of transfer station resilience characteristics is represented in Figure 3.

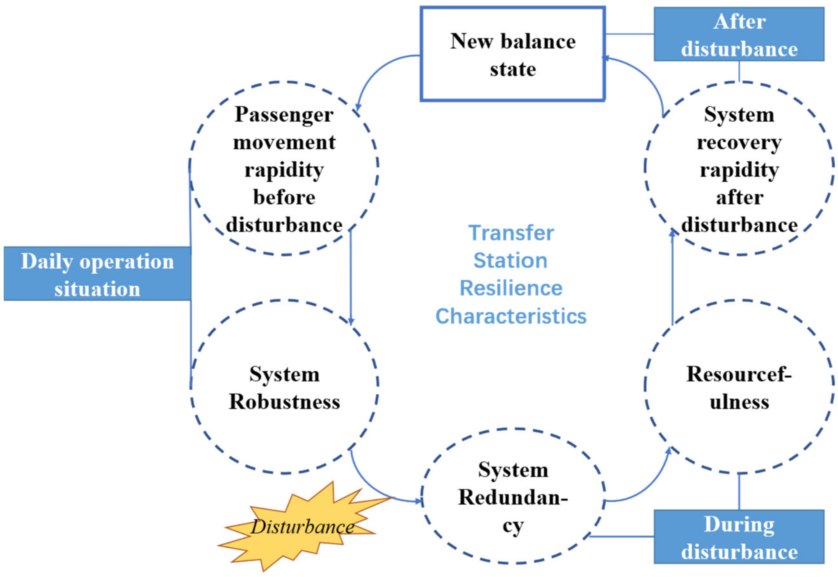


Figure 3. Resilience characteristic acting process.

According to the resilience characteristics, the resilience components of each characteristic are summarized as two-level factor sets. There are five factors in the first-level factor set and nine factors in the second-level factor set. The factor sets and their symbolic representations are illustrated in Figure 4.

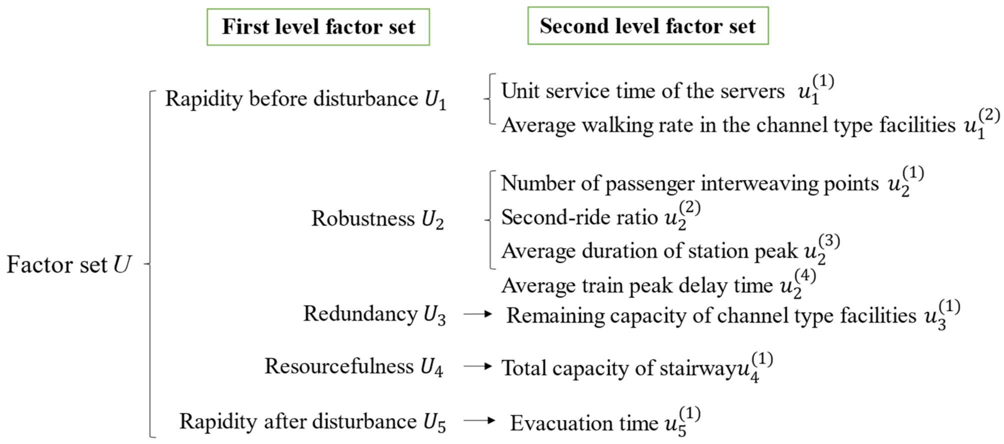


Figure 4. Factor sets in the comprehensive evaluation model.

3.1.2. Determining the Review Set

A review set comprises the words used in the fuzzy comprehensive evaluation method to evaluate each index, which is mainly set according to the nature of the evaluation object. This paper assumes that the review set $V = \{v_1, v_2, v_3, v_4, v_5\}$, where v_1, v_2, v_3, v_4, and v_5 present the resilience level of the transfer station as very good, good, medium, poor, and very poor, respectively.

3.1.3. Calibrating the Weights

Although the order relation distinguishing method(the G1 method [21]) is prone to situations where multiple relatively unimportant indicators have equal weights, the G1 method can be used to solve problems in the fuzzy set category and is applicable to the method of fuzzy comprehensive evaluation used in this paper. It is also able to combine quantitative ranking and qualitative scaling to improve scientific validity. Compared to other weighting methods, this method is more objective and uses fewer resources to calibrate the weights when most of the information is unknown.

Therefore, this paper adopts the G1 method to calibrate the weight of the first-level factors and the second-level factors.

1. Calibrating the weights of the first-level factors

   (1) Determination of the importance order of each factor

We assume that the resilience of the transfer station is R, and the corresponding first-level factors are U_1, U_2, U_3, U_4, and U_5. If the importance of U_i is greater than U_j under a certain evaluation criterion, it is recorded as $U_i \succ U_j$. We obtain the importance rank of each factor according to the following steps: (a) choose the most important factor from the five factors, and record it as U_1^*; (b) choose the most important factor from the remaining four factors and record it as U_2^*; repeat (b) until the last indicator, U_5^*, is ranked.

This work adopts the idea of the Delphi method [22]. We invited two university professors of urban rail and an engineer of an urban rail operating company to rank the importance, and the ranking table is placed in the Appendix A at the end of our article; after five rounds of adjustment, we obtained the importance ranking for the five first-level factors as follows: $U_5 > U_2 > U_4 > U_3 > U_1$. The corresponding indicators and marks are shown in Table 1.

Table 1. Importance ranking of the first-level factor.

Importance Ranking	**1**	**2**	**3**	**4**	**5**
Marking	$U_1^*(U_5)$	$U_2^*(U_2)$	$U_3^*(U_4)$	$U_4^*(U_3)$	$U_5^*(U_1)$
Factor	Rapidity after disturbance	Robustness	Resourcefulness	Redundancy	Rapidity before disturbance

   (2) Judgement of the importance ratio

According to the order of importance among the factors judged in the previous step, the importance is further quantified below. Supposing the importance ratio of U_{k-1}^*/U_k^* is ω_{k-1}/ω_k (the ratio of weight), the ratio can be calculated as follows:

$$\frac{\omega_{k-1}}{\omega_k} = r_k \ (k = 2,\ 3,\ 4,\ 5) \tag{1}$$

where r_k is the tone operator. At present, the nine-level operator method is commonly used. The tone operators are shown in Table 2.

Table 2. Representation of tone operators.

r_k	Notation
1.0	U_k^*, U_{k-1}^* are equally important
1.1	U_k^*, U_{k-1}^* is between equally important and slightly important
1.2	U_k^*, U_{k-1}^* is slightly important
1.3	U_k^*, U_{k-1}^* is between slightly important and obviously important
1.4	U_k^*, U_{k-1}^* is obviously important
1.5	U_k^*, U_{k-1}^* is between obviously important and strongly important
1.6	U_k^*, U_{k-1}^* is strongly important
1.7	U_k^*, U_{k-1}^* is between strongly important and extremely important
1.8	U_k^*, U_{k-1}^* is extremely important

Rounded to the nearest whole number based on the average of the experts' scores, the importance ratios for the first-level factors are shown in Table 3.

Table 3. Importance ratios of the first-level factors.

Importance Ratio	Value
r_2	1.2
r_3	1.4
r_4	1.2
r_5	1.2

(3) Calculation of the weights

We calculate the weight of the fifth important first-level factor, i.e. weight of rapidity after disturbance, using Formula (2):

$$\omega_5 = \left(1 + \sum_{k=2}^{5} \prod_{i=k}^{5} r_i\right)^{-1} \tag{2}$$

We obtain the weight of the remaining factors according to formula $\omega_{k-1} = r_{k-1}\omega_k$. The weights of the five first-level factors are calculated as shown in Table 4.

Table 4. Weights of the first-level factors.

Factor	Weight
Rapidity after disturbance U_5	0.2996
Robustness U_2	0.2497
Resourcefulness U_4	0.1783
Redundancy U_3	0.1486
Rapidity before disturbance U_1	0.1238

2. Calibrating the weights of the second-level factors

The method used for determining the weights of the first-level indicators is also adopted for each secondary factor. Rapidity before disturbance and robustness each have their own set of secondary indicators.

(1) For the second-level factors of rapidity before disturbance

According to the experts' judgment, the unit service time of the servers is as important as the average walking rate in the station's channel-type facilities. Therefore, the two secondary factors are equally important: their weights under rapidity before disturbance are both 0.5.

(2) For the second-level factors of robustness

1) Determination of the importance order of each factor

The evaluation object is the robustness of the transfer station, and the corresponding secondary factors are $u_2^{(1)}, u_2^{(2)}, u_2^{(3)}$, and $u_2^{(4)}$, which are obtained through the same steps taken to determine the importance order of the first-level factors. According to the experts' judgment, the importance order of the secondary factors corresponding to robustness is $u_2^{(4)} > u_2^{(2)} > u_2^{(3)} > u_2^{(1)}$. The corresponding indicators and marks are shown in Table 5.

Table 5. Importance ranking of the second-level factors of robustness.

Importance Ranking	**1**	**2**	**3**	**4**
Marking	$U_1^*\left(u_2^{(4)}\right)$	$U_2^*\left(u_2^{(2)}\right)$	$U_3^*\left(u_2^{(3)}\right)$	$U_4^*\left(u_2^{(1)}\right)$
Factor	Average train peak delay time	Second-ride ratio	Average duration of station peak	Number of passenger interweaving points

2) Judgement of the importance ratio

According to the order of importance among the factors judged in the previous step, the importance is further quantified below. Supposing the importance ratio of U_{k-1}^*/U_k^* is ω_{k-1}/ω_k (the ratio of weight), the ratio is calculated as follows:

$$\frac{\omega_{k-1}}{\omega_k} = r_k \ (k = 2,\ 3,\ 4) \tag{3}$$

According to the experts' scores, the importance ratios r_k are shown in Table 6.

Table 6. Importance ratios of the second-level factors of robustness.

Importance Level Ratio	**Value**
r_2	1.5
r_3	1
r_4	1

3) Calculation of the weight

We calculate the weight of the fourth important factor using Formula (4):

$$\omega_4 = \left(1 + \sum_{k=2}^{4} \prod_{i=k}^{4} r_i\right)^{-1} \tag{4}$$

Then, the weight of ω_3 is determined as $\omega_3 = r_3\omega_4$. According to $\omega_{k-1} = r_{k-1}\omega_k$. The weights for the average train peak delay time, second-ride ratio, average duration of station peak, and number of passenger interweaving points are 0.34, 0.22, 0.22, and 0.22, respectively.

Summarizing the above, the weight of each factor is displayed in Table 7.

Table 7. Weights of first- and second-level factors.

First-Level Factor Weight	**Second-Level Factor Weight**
Rapidity before disturbance U_1 0.1238	Queuing system unit service time $u_1^{(1)}$ 0.5 Average walking rate in channel-type facilities $u_1^{(2)}$ 0.5

Table 7. *Cont.*

First-Level Factor Weight	Second-Level Factor Weight
Robustness U_2 0.2497	Number of passenger interweaving points $U_4^*\left(u_2^{(1)}\right)$ 0.22 Second-ride ratio $U_2^*\left(u_2^{(2)}\right)$ 0.22 Average duration of station peak $U_3^*\left(u_2^{(3)}\right)$ 0.22 Average train peak delay time $U_1^*\left(u_2^{(4)}\right)$ 0.34
Redundancy U_3 0.1486	Average coefficient of the facilities' remaining capacity $u_3^{(1)}$ 1.0
Resourcefulness U_4 0.1783	Total capacity of stairways $u_4^{(1)}$ 1.0
Rapidity after disturbance U_5 0.2996	Evacuation time $u_5^{(1)}$ 1.0

3.1.4. Determining the Membership Degree Matrix

To obtain the membership degree matrix, first, the membership of the second-level factor sets $U_i = \left\{u_i^{(1)}, u_i^{(2)}, \ldots, u_i^{(n)}\right\}$ for the review set $V = \{v_1, v_2, v_3, v_4, v_5\}$ is comprehensively evaluated. The membership degree value indicates the closeness of each secondary evaluation target to each element in the review set, with this value ranging between 0 and 1. The higher the membership degree of the evaluation target to an element in the review set, the more the comment in the review set can be used to evaluate the factor. Table 8 presents the corresponding evaluation membership values of the resilience evaluation system established in this paper for URT transfer stations.

Table 8. The membership values corresponding to the comments.

Comment	Membership Value
Particularly good	$0.8 \leq V < 1.0$
Good	$0.6 \leq V < 0.8$
Medium	$0.4 \leq V < 0.6$
Poor	$0.2 \leq V < 0.4$
Extremely poor	$0 \leq V < 0.2$

There are many methods available to determine the membership degree, such as the fuzzy statistics method, the existing objective scale method, and the assignment method. In this paper, we use the existing objective scale method to determine the membership degree.

Comprehensively considering the characteristics of each evaluation index and its corresponding range of values, we directly establish the membership degree matrix R_i of the secondary factor set $U_i = \left\{u_i^{(1)}, u_i^{(2)}, \ldots, u_i^{(n)}\right\}$ corresponding to the review set $V = \{v_1, v_2, v_3, v_4, v_5\}$.

$$R_i = \begin{bmatrix} r_{11}^{(i)} & r_{12}^{(i)} & r_{13}^{(i)} & r_{14}^{(i)} & r_{15}^{(i)} \\ r_{21}^{(i)} & r_{22}^{(i)} & r_{23}^{(i)} & r_{24}^{(i)} & r_{25}^{(i)} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ r_{n1}^{(i)} & r_{n2}^{(i)} & r_{n3}^{(i)} & r_{n4}^{(i)} & r_{n5}^{(i)} \end{bmatrix}$$

Among the factor sets, there are the time-type, rate-type, and percentage-type factors, etc., and their dimensions and units are not uniform. In order to avoid the distortion of the evaluation results and calculate the membership value of each index quantitatively, it is necessary to normalize each index and transform the attribute value of each index into the [0, 1] interval. For the maximal index, the minimal index, and the intermediate index, the normalization formula is different. The conversion formula for the maximum index is

$$y_{ij} = \frac{x_{ij} - min_{ij}}{max_{ij} - min_{ij}} \quad (5)$$

The conversion formula for the minimum indicators is

$$y_{ij} = \frac{max_{ij} - x_{ij}}{max_{ij} - min_{ij}} \quad (6)$$

Interval indicators such as speed need to be converted into maximum indicators first, and the conversion formula is

$$x_{ij} = \begin{cases} 1 - \frac{a-x}{M},\ x < a \\ 1,\ a \le x \le b \\ 1 - \frac{x-b}{M},\ x > b \end{cases}, \quad (7)$$

Then, Formula (8) is used to normalize it and obtain the final membership value, where x_{ij} represents the original data and y_{ij} represents the normalized data; max_{ij} and min_{ij} are the maximum value and minimum value of the threshold range, as shown in Table 9.

$$M = \max\{a - \min\{x_i\}, \max\{x_i\} - b\} \quad (8)$$

Table 9. Threshold of each evaluation index.

Index	Index Type	Threshold Range	Source
Unit service time of the servers	Minimum	5–80 s	Anylogic average value
Average walking rate in channel-type facilities	Interval	0.51–0.79 (m/s)	References [23–25]
Number of passenger interweaving points	Minimum	0–15	Investigation
Second-ride ratio	Minimum	0–1	Percentage
Average duration of station peak	Interval	30–90 min	Investigation
Average train peak delay time	Minimum	0–60 s	Investigation
Remaining capacity of channel-type facilities	Maximum	0–1	Percentage
Total capacity of stairways	Maximum	0–12,900 person/h	Reference [26]
Evacuation time	Minimum	0–6 min	Reference [26]

To determine the maximum value max_{ij} and minimum value min_{ij} of the original data for each evaluation index, we determine the threshold values based on the existing literature, field investigations, and data types, as shown in Table 9.

If the weight of $U_i = \left\{u_i^{(1)}, u_i^{(2)}, \ldots, u_i^{(n)}\right\}$ is $A_i = \left\{a_i^{(1)}, a_i^{(2)}, \ldots, a_i^{(n)}\right\}$, then the comprehensive judgement is $B_i = A_i \cdot R_i (i = 1, 2, \ldots, k)$.

3.1.5. Comprehensive Evaluation

After calibrating the weights and membership degrees, we comprehensively judge the first-level factors, $U = \{U_1, U_2, U_3, U_4, U_5\}$, and the weight set, A = {0.1238, 0.2497, 0.1486, 0.1783, 0.2996}, thus we obtain the membership degree matrix R_i, as follows:

$$R = [B_1, B_2, B_3, B_4]^T \quad (9)$$

Then, the comprehensive judgement is

$$B = A \cdot R \quad (10)$$

Finally, we obtain the result of this comprehensive judgement, where the value with the largest membership degree corresponding to the review set represents the resilience level of the transfer station.

3.2. Resilience Components and the Calculation Method

In transfer stations, since there are more intertwined flows in the paid area, which affects the travel speed of the passengers, and most of the flows are transfer flows, the passenger density and travel speed in channel-type facilities such as escalators and stairs are greatly affected. This is the biggest difference between transfer stations and non-transfer stations; so, the model developed in this paper is specially designed for transfer stations and cannot be extended to non-transfer stations.

3.2.1. Rapidity Components before Disturbance

1. Queuing system unit service time *UST*

The unit service time (*UST*) of the queuing system is used to express the rapidity of passengers on the queuing system before disturbance, which is the sum of the service time at the queuing system of the inbound process as *UST*, which can be calculated directly by using simulation software.

2. Average walking rate in channel-type facilities

For channel-type facilities, the average travel rate in channels is defined to evaluate the rapidity before disturbance. The channels here include stairways and corridors, which can be calculated directly by using simulation software.

3.2.2. Robustness Components

Robustness refers to the ability of the transfer station system to resist disturbance, which is the basis of system resilience.

1. Number of passenger interweaving points N_w

The number of passenger interweaving points indicates the number of points where passenger trajectories conflict in the transfer area, excluding the conflicting trajectories outside the entrance and exit ticket-checking gates, which can be obtained according to the passenger flow organization streamline.

2. Second-ride ratio

After passengers arrive at the platform, there may be three kinds of boarding situations: The first is when they arrive at the platform and the train is open with available seats, so the passengers can board directly. The second is when the passengers arrive at the platform but the train has not yet arrived, so they need to wait; however, once the train arrives and there are available seats, the passengers can then board directly. The third occurs if the first train is full upon its arrival at the platform, so the passengers need to wait for the next available train. These subsequent trains could either be the immediate next one or the *n*th one following. In this paper, this scenario is defined as the second ride. The calculation formula for the second-ride ratio is

$$P_t = \frac{N_s}{N_s + N_d} \tag{11}$$

where N_s is the number of passengers who take the second ride, which can be obtained through simulation or field investigations. N_d is the number of passengers who can take the first train upon its arrival at the platform.

3. Average duration of station peak

Reference [26] points out that "It is assumed that 37% to 47% of the peak hourly passenger flow is passed within 20 min of the peak, so the over-peak factor is 1.1 to 1.4". In this paper, the average duration of the station peak is obtained with the help of the percentage of over-peak passenger flow. First, we count the passenger flows inbound and outbound of the station within 20 min of the peak, and back-calculate the passenger flow throughout the duration of the peak according to the passenger flow during this 20 min; the specific formula for this is

$$N_{peak} = \frac{N_{20\mathrm{min}}}{37\%} \tag{12}$$

Within this formula, N_{peak} is the total passenger flow during the over-peak hours, which is obtained through passenger flow data statistics. $N_{20\mathrm{min}}$ is the number of passengers passing during the 20 min over-peak period, obtained from passenger flow statistics. As

37~47% is the ratio of the over-peak-hour passenger flow to the total peak-hour passenger flow in reference [26], a conservative value 37% is selected.

After obtaining the total passenger flow during peak hours, the time spent in passing the total peak passenger flow N_{peak} is counted as T_{con}. The specific graph for this is shown in Figure 5.

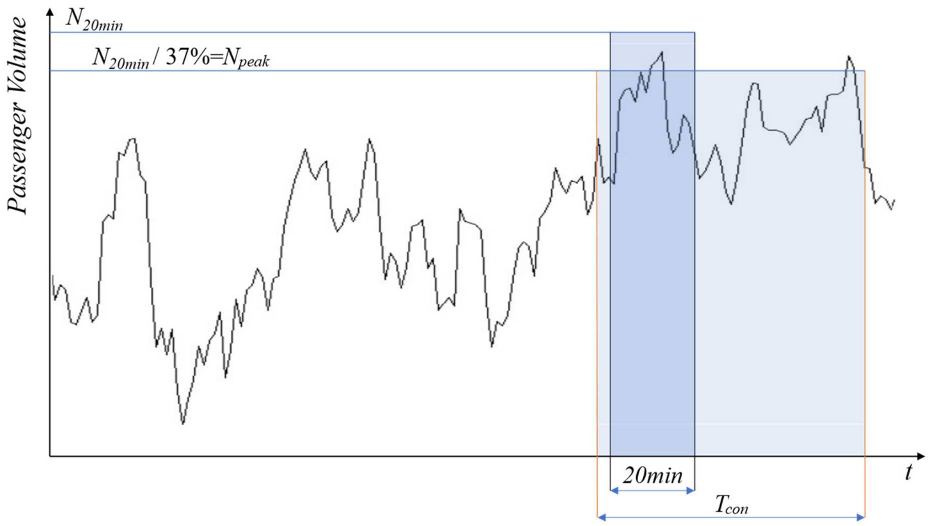


Figure 5. Graphical representation of the average duration of the station's peak period.

4. Average train peak delay time T_{delay}

For a rail transit system, the core element is the trains. The arrival and departure of a train can accommodate a large number of passengers, but trains are always subject to delays due to various emergency disturbances. Even a slight delay during rush hour can exert significant pressure on transfer stations. Therefore, the average delay time of the peak trains is also a critical component of robustness. Unit: s.

3.2.3. Redundancy Components

The redundancy index indicates the remaining service capacity of the transfer station's equipment and facilities, which can ensure the normal operation of the transfer station in a certain range when encountering a sudden passenger flow.

1. Coefficient of channel-type facilities' remaining capacity *CCRC*

Table 10 lists some capacities of channel-type facilities in metro stations given in [26].

Table 10. Maximum capacities of channel-type facilities.

Part Name		Maximum Capacity (Person-Time/h)
1 m wide stairs	Going down	4200
	Going up	3700
	Bidirectional mixed line	3200
1 m wide channel	One-way	5000
	Bidirectional mixed line	4000
1 m wide escalator	The conveying speed is 0.5 m/s	6720
	The conveying speed is 0.65 m/s	Less than 8190
0.65 m wide escalator	The conveying speed is 0.5 m/s	4320
	The conveying speed is 0.65 m/s	5265

The expression for the coefficient of the channel facilities' remaining capacity is as follows:

$$CCRC = 1 - (Sat_{stair} + Sat_{escalator} + Sat_{channel})/3$$
$$CCRC = 1 - \left(\frac{V_{stair}}{C_{stair}} + \frac{V_{escalator}}{C_{escalotor}} + \frac{V_{channel}}{C_{channel}}\right)/3 \tag{13}$$

where Sat_{stair}, $Sat_{escalator}$, and $Sat_{channel}$ are the saturation of stairs, escalators, and channels, respectively. V_{stair}, $V_{escatotor}$, and $V_{channel}$ are the total number of passengers passing through stairs, escalators, and channels during peak hours, respectively, which are obtained through simulation. Unit: person/h. C_{stair}, $C_{escatotor}$, and $C_{channel}$ are the maximum capacity of the stairs, escalators, and channels, respectively. Unit: person/h.

2. Coefficient of distributed facilities' remaining capacity *CDRC*

The remaining capacity of distributed facilities refers to the total number of passengers that can be accommodated in the available standing area in the station hall and on the platforms during peak hours. After reviewing previous papers [23–25], the average passenger density and speed under different levels of service (LOSs) for the station hall, platform walking areas, and waiting areas are concluded in Table 11.

Table 11. Index values under different service levels.

Region	Index	A	B	C	D	E
Station hall	Passenger density (p/m^2)	<0.30	0.30–0.56	0.56–1.16	1.16–2.05	>2.05
Platform waiting area	Passenger density (p/m^2)	<0.84	0.84–1.56	1.56–1.93	1.93–3.52	>3.52
Platform walking area	Passenger density (p/m^2)	<0.30	0.30–0.56	0.56–1.16	1.16–2.05	>2.05
	Passenger speed (m/s)	>1.31	1.10–1.31	0.79–1.10	0.51–0.79	<0.51

It is pointed out in [26] that when designing the platform width, the average area occupied per person ranges from 0.33 m^2 to 0.75 m^2. Correspondingly, the LOS for the waiting area is classified as C, while for the walking area, it is classified as D. Therefore, grades C and D are considered as the anticipated service levels for the waiting area and the walking area, respectively. Since the passenger density on the platform is generally higher than that in the station hall, the LOS of the station hall is inferred from the platform LOS, thus we take the LOS of the station hall as D.

Under the expected service level mentioned above, and considering the median pedestrian density, the pedestrian density in the station hall is 1.61 person/m^2, in the waiting area is 1.75 person/m^2, and in the walking area is 1.61 person/m^2, with a walking speed of 0.65 m/s. The expression for *CDRC* is as follows:

$$CDRC = 1 - \left(Sat_{hall} + Sat_{platform}\right)/2$$
$$CDRC = 1 - \left(\frac{\max\{P_{hall}\}}{S_{hall} \cdot \rho_{hall}} + \frac{\max\{P_{platform}\}}{S_{platform} \cdot \rho_{platform}}\right)/2 \tag{14}$$

Since the platform is divided into the waiting area and walking area, the $Sat_{platform}$ is

$$Sat_{platform} = \frac{\max\{P_{walking}\}}{S_{walking} \cdot \rho_{walking}} + \frac{\max\{P_{waiting}\}}{S_{waiting} \cdot \rho_{waiting}} \tag{15}$$

where Sat_{hall} and $Sat_{platform}$ indicate the passenger saturation of the station hall and platform, respectively; P_{hall} and $P_{platform}$ are the maximum number of passengers during rush hour in the station hall and on the platform, respectively; ρ_{hall} and $\rho_{platform}$ are the intermediate values of passenger density corresponding to the expected service level in the station hall and on the platform, respectively; $\rho_{waiting}$ and $\rho_{walking}$ are the intermediate values of passenger density corresponding to the expected service level in the waiting area and the walking area, respectively; S_{hall} and $S_{platform}$ are the net areas of the station hall and platform, respectively (excluding the effective areas of various facilities, columns, and buildings); $S_{waiting}$ and $S_{walking}$ are the net areas of the waiting area and walking area, respectively.

3.2.4. Resourcefulness Components

After reviewing the literature [23–25], it is found that the passenger flow density in a transfer station follows a certain order: stair-type equipment > platform > station hall > channel. Therefore, this paper focuses solely the resourcefulness of stairways. Stairways include stairs, escalators, and elevators, which complement each other in daily use. However, in the event of a disturbance, passengers need to evacuate, and each stairway should strive to fulfill its role effectively. Table 12 shows the classification of passenger flow densities under different LOSs of stair-type equipment.

Table 12. Stair-type facility passenger densities under different LOSs.

Region	LOS	A	B	C	D	E
Stairs	Passenger density (p/m^2)	<0.51	0.51–0.79	0.79–1.16	1.16–1.82	>1.82
Escalators	Passenger density (p/m^2)	<0.45	0.45–2.06	2.06–1.14	1.14–1.41	>1.41

Then, the expression for the total capacity of the stair-type facilities is

$$TC_{sf} = S_{stair} \cdot \rho_{stair} + S_{escalator} \cdot \rho_{escalator} + C_{elevator} \tag{16}$$

where S_{stair} and $S_{escalator}$ are the areas of stairs and escalators, respectively. ρ_{stair}, $\rho_{escalator}$ are the expected service levels of stairs and escalators, respectively. During evacuation, passengers are evacuated at maximum density, typically corresponding to the lowest service level. $C_{elevator}$ stands for the number of passengers carried by the elevator.

3.2.5. Rapidity Components after Disturbance

For the evacuation time after disturbance, this paper adopts the calculation method in reference [26], using the emergency evacuation time T, which is the time taken for passengers to evacuate from the platform to a public area or other safe areas in the station hall in the long term or in the peak hours during the passenger flow control period.

Then, the time T taken for an evacuation from the platform to the station hall is expressed as

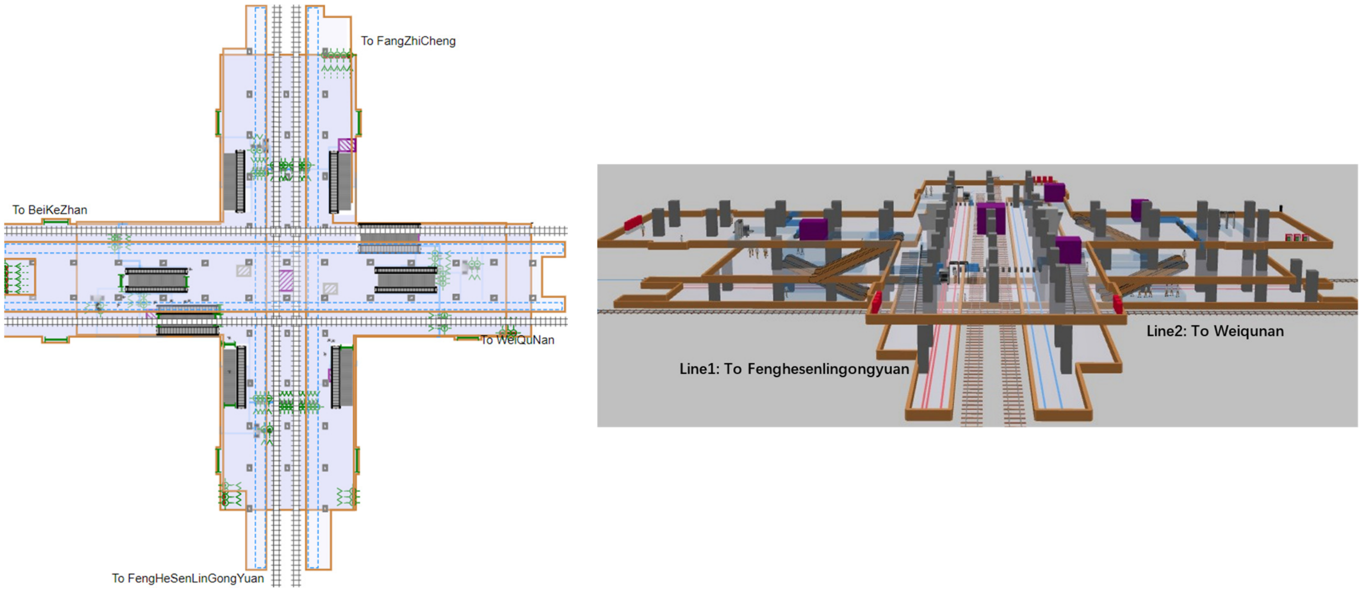
$$T = 1 + \frac{Q_1 + Q_2}{0.9[A_1(N-1) + A_2 B]} \tag{17}$$

where T is the evacuation time from the platform level to the station hall level, as given in reference [26]; Q_1 is the maximum passenger cross-sectional flow (person) of one incoming train during the over-peak hour in the long term or passenger flow control period; Q_2 is the maximum number of passengers waiting on the platform during the over-peak hour in the long term or passenger flow control period (person); A_1 is the passing capacity for one escalator (person/min·m); A_2 is the passing capacity for evacuation stairs (person/min·m); N is the number of escalators; and B is the total width of the evacuation stairs (m), where the width of each group of stairs should be calculated as an integer multiple of 0.55 m.

4. Case Study

4.1. Overview of the Bei-Da-Jie Transfer Station

Bei-Da-Jie Station is the transfer station between Xi'an Metro Line 1 and Line 2, located in Lianhu District, Xi'an. Through processing AFC (Automatic Fare Collection) data and OD data, we calculated the peak hour of this station to be 8:00–9:00 a.m. and used this to research and carry out field investigations to obtain the passenger flows, train departure intervals, the number of entrance and exit ticket-checking gates, etc. Then, the establishment of a model in Anylogic 8.7.0 for Bei-Da-Jie Station could be divided into three steps: station environment construction, pedestrian logic modeling, and train flow modeling. The 2D and 3D modeling results for Bei-Da-Jie Station are shown in Figure 6a,b, respectively.



(**a**) (**b**)

Figure 6. Two- and three-dimensional diagrams of the Bei-Da-Jie transfer station. (**a**) Two-dimensional diagram; (**b**) Three-dimensional diagram.

4.2. Calculating the Peak-Hour Resilience Components

4.2.1. Calculation Results for the Sub-Items

We input the peak-hour data into Anylogic 8.7.0 using the calculation method given in Section 3.2 to obtain the assessment value of each resilience component. These calculation results are shown in Table 13.

Table 13. Summary table of evaluation index values.

Index	Threshold Range	Value	Score
Queuing system unit service time	5–300 s	897.6 s	0
Average walking rate in the channels	0.51–0.79 (m/s)	0.108 m/s	0
Number of passenger interweaving points	0–15	12	0.2
Second-ride ratio	0–1	0.34	0.66
Average duration of station peak	30–90 min	135 min	0
Average train peak delay time	0–60 s	34 s	0.43
Remaining capacity of channel-type facilities	0–1	0.5398	0.54
Total capacity of stairways	0–12,900 person/h	104,596 person/h	1
Evacuation time	0–6 min	9.60 min	0

4.2.2. Comprehensive Resilience Assessment for Bei-Da-Jie Station during its Peak Hour

If we take the weight of $U_1 = \left\{u_1^{(1)}, u_2^{(1)}\right\}$ as $A_1 = \{0.5, 0.5\}$, then the comprehensive judgment is $B_1 = A_1 \cdot R_1$. Then, B_1 is

$$B_1 = [0.5\ 0.5] \times \begin{bmatrix} 0 \\ 0 \end{bmatrix} = 0 \tag{18}$$

Using the same method above, calculating the remaining B values gives $B_2 = 0.3222$, $B_3 = 0.5398$, $B_4 = 1.0$, and $B_5 = 0$. Then, the comprehensive judgment is

$$R = [0\ 0.3222\ 0.5398\ 1.0\ 0]^T \tag{19}$$

Then, the first-level factors $U = \{U_1, U_2, U_3, U_4, U_5\}$ are comprehensively judged, and the weight set is $A = \{0.1238,\ 0.2497,\ 0.1486,\ 0.1783,\ 0.2996\}$,

$$B = A \cdot R = [0.1238\ 0.2497\ 0.1486\ 0.1783\ 0.2996] \cdot R = 0.3425 \tag{20}$$

As the result is 0.3425, the resilience of Bei-Da-Jie Station corresponding to the review set is "Poor". If the transfer station is at this resilience level for a long period of time during the peak hour, it will struggle to cope with complex disturbance scenarios, which is not conducive to the sustainability of urban mobility.

4.3. Resilience Curve of Bei-Da-Jie Station under Different Passenger Numbers

4.3.1. Passenger Input and Corresponding Output

Firstly, we input the peak-hour passenger number with different multipliers into the transfer station simulation system to obtain data in the same way as described in Section 4.2 and calculate the resilience values of corresponding level of passenger flow, as shown in Table 14.

Table 14. Resilience under different peak-hour passenger multipliers.

Multi-Plier	Rapidity before Disturbance		Robustness				Redundancy		Resourcefulness	Rapidity after Disturbance	Resilience Value
	UST	Average Walking Rate	Interweaving Points	Second-Ride Ratio	Peak Duration	Train Delay	CDRC	CCRC	Stair Total Capacity	Evacuation Time	
0.05	54	0.55	12	0	135	0	0.98	0.99	164	1.90	0.7635
0.1	52.2	0.551	12	0	135	0	0.96	0.99	164	2.31	0.7427
0.15	52.2	0.546	12	0	135	0	0.94	0.98	164	2.71	0.7205
0.2	54	0.691	12	0	135	0	0.92	0.97	164	3.12	0.6967
0.25	52.8	0.75	12	0	135	0	0.90	0.96	164	3.52	0.6756
0.3	58.8	0.742	12	0	135	0	0.89	0.96	164	3.93	0.6490
0.35	57.6	0.476	12	0	135	0	0.87	0.94	164	4.33	0.6223
0.4	67.2	0.373	12	0	135	0	0.85	0.93	164	4.74	0.5761
0.45	82.2	0.242	12	0	135	0	0.85	0.91	164	5.14	0.5233
0.5	166.8	0.219	12	0	135	0	0.80	0.89	164	5.55	0.4946
0.55	345	0.184	12	0	135	0	0.78	0.88	164	5.95	0.4666
0.6	354.6	0.161	12	0.01	135	1	0.73	0.85	164	>6	0.4528
0.65	353.4	0.15	12	0.01	135	1	0.69	0.85	164	>6	0.4480
0.7	523.8	0.135	12	0.02	135	2	0.63	0.83	164	>6	0.4381
0.75	624.6	0.129	12	0.03	135	3	0.59	0.84	164	>6	0.4322
0.8	627	0.123	12	0.05	135	5	0.52	0.83	164	>6	0.4218
0.85	750	0.114	12	0.08	135	8	0.44	0.82	164	>6	0.4083
0.9	697.8	0.12	12	0.13	135	13	0.38	0.82	164	>6	0.3945
0.95	862.8	0.11	12	0.21	135	21	0.32	0.81	164	>6	0.3720
1	897.6	0.108	12	0.34	135	34	0.28	0.80	164	9.60	0.3425

Among these values, when considering the passenger characteristics, the second-ride ratio and train delay values larger than the 0.6 multiplier are expressed as 0.01 times and 1 times the Fibonacci sequence, respectively.

4.3.2. Obtaining the Resilience Curve of Bei-Da-Jie Station

After obtaining the resilience under different peak-hour passenger multipliers, multiples of the peak-hour passenger number are interpolated with the actual passenger flow data to obtain the time of occurrence of each multiple of the passenger flow. According to the actual passenger flow data, 8:00–9:00 is the morning peak; then, from 6:00., when the URT starts to operate, until 9:00. the disturbance–resistance process of the transfer station occurs, which is expressed as 0–180 min on the coordinate axis. The evening peak occurs at 18:00–19:00.; then, from 18:00. until the end of the URT operations, i.e., 24:00., is the recovery period of the transfer station, which is expressed as 180–540 min on the coordinate axis. Since both the 0.95 and 1.0 passenger count multipliers are higher than the evening peak, these two data points are omitted. Then, linear interpolation, quadratic interpolation, and cubic interpolation are used and averaged to obtain the time of occurrence of different passenger flows on the coordinate axes. According to the interpolation results, the time corresponding to the backward interpolation result for the 0.9 passenger flow data multiplier in the evening peak is approximated to be 180 min, and this data point is also omitted.

Thus, the corresponding resilience values at different multipliers and times are shown in Table 15, as follows.

Table 15. Resilience values corresponding to times under different passenger levels.

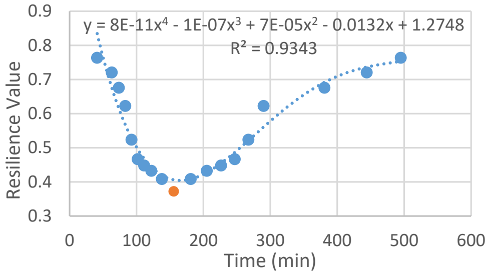
Multiplier	Passenger Number	Disturbance Process Time	Recovery Process Time	Resilience Value
0.05	686	41.21	494.98	0.7635
0.1	1373	54.41	466.95	0.7427
0.15	2059	63.20	444.17	0.7205
0.2	2745	68.63	419.81	0.6967
0.25	3432	73.76	380.95	0.6756
0.3	4118	78.67	311.04	0.6490
0.35	4804	83.40	289.93	0.6223
0.4	5491	88.02	277.95	0.5761
0.45	6177	92.56	267.35	0.5233
0.5	6864	97.15	257.10	0.4946
0.55	7550	101.81	246.94	0.4666
0.6	8236	106.56	236.76	0.4528
0.65	8923	111.44	226.47	0.4480
0.7	9609	116.47	215.99	0.4381
0.75	10,295	122.37	205.19	0.4322
0.8	10,982	129.99	193.79	0.4218
0.85	11,668	137.96	181.19	0.4083
0.9	**12,354**	138.79	180.00	0.3945
0.95	**13,041**	155.84	\	0.3720
1.0	**13,727**	180.00	\	0.3425

We used multipliers that are odd multiples of 0.05 as the training set and the remaining data as the test set. We performed polynomial fitting using the training set and found that the fitting effect was better when the order was set to 4. The expression of the resilience function for the training set is as follows:

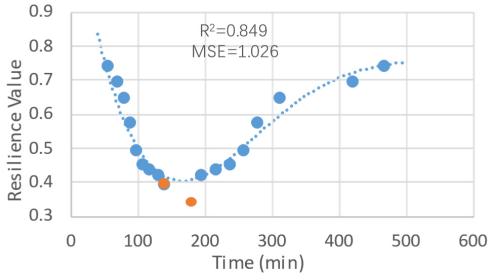
$$y = 8 \times 10^{-11} x^4 - 1 \times 10^{-7} x^3 + 7 \times 10^{-5} x^2 - 0.0132x + 1.2748 \tag{21}$$

The goodness of fit R^2 of the training set resilience function is 0.9343, and for the test set, the goodness of fit R^2 is 0.849, which indicates that the fit is generally accurate. Plotting this quadratic polynomial image reveals that it provides a more accurate representation of transfer station resilience when the time is greater than 40 min; thus, the polynomial can be used to calculate the resilience value of the transfer station from 40 min after the start of an operational peak cycle. For the test set, observing the fit of the test set according to the training set's fitting equation (Formula (21)) using the mean squared error (MSE), we obtain an MSE of 1.026, which is an acceptable value.

The curves of the training set and test set are shown in Figure 7a,b, respectively. The trend of the resilience curves in Figure 7 is generally consistent with that in Figure 1, which verifies that the application of the fuzzy comprehensive evaluation model is appropriate. Management staff can implement relevant control measures for this transfer station based on resilience requirements. As shown Figure 7, when the number of passengers in the transfer station is greater than 12,000 (orange dots in Figure 7), the resilience level of the transfer station reaches the "poor" level in the review set. Therefore, passenger-flow-monitoring facilities can be installed to implement some flow control measures when the passenger flow in the transfer station is greater than 12,000 to enhance the sustainability of the development of the transfer station.



(**a**)



(**b**)

Figure 7. Time-resilience curves: for training set and test set. (**a**) Train Result; (**b**) Validation Result.

4.4. Measurements for Improving the Resilience of Bei-Da-Jie Transfer Station

It can be seen from the calculation results in Section 4.2 that the resilience level of Bei-Da-Jie Station during its peak hour is "poor," which indicates that the resilience and comprehensive anti-disturbance ability of Bei-Da-Jie Station need to improve, especially its ability to recover from disturbance. Here, the weighting and scoring results are combined to determine a resilience improvement prioritization strategy that can be referenced for Bei-Da-Jie Station. Table 16 shows some improvement priority suggestions that Xi'an URT management departments can adopt to improve the sustainability of transfer stations as well as URT networks.

Table 16. Resilience improvement methods and improvement prioritization strategies.

Priority	Index	Level	Improvement Measurements
2	Rapidity before disturbance	Very Poor	(a) Improve the service ability of servers (b) Guide passengers through signs or the help of personnel
3	Robustness	Poor	(a) Use some measures to improve passenger guidance (b) Implement passenger flow restriction during peak hour
4	Redundancy	Medium	Implement passenger flow restriction during peak hour
5	Resourcefulness	Very good	Preserve the status quo
1	Rapidity after disturbance	Very poor	(a) Station control (b) Line control (c) Network control (d) Guide passengers to partially evacuate other stations along the line in advance

5. Conclusions and Discussion

5.1. Conclusions

Based on simulation analyses, this paper develops a quantitative evaluation method for evaluating the resilience of URT transfer stations. Based on the existing research on resilience and the study of URT, this paper puts forward resilience characteristics based on the resilience development stage of transfer stations, and then puts forward a resilience assessment model and applies it to Xi'an Bei-Da-Jie Station to determine this transfer station's resilience level, thereby validating the model's applicability. The main contributions of this study are as follows:

1. By combining existing research, this paper proposes the resilience characteristics suitable for transfer stations and their corresponding development stages based on the specific characteristics of transfer stations.
2. This paper proposes a model to quantitatively assess the resilience of transfer stations, as this is still a research gap. This model was applied to a representative transfer station to evaluate its resilience under different passenger flow conditions, proving the practicality of the proposed model. The fitted resilience curve for this transfer station is also consistent with that of the resilience development stage, as shown in Figure 1. This model can also be applied to most urban rail transit transfer stations, which shows that it has strong universality and practical significance.
3. The results of our evaluation can provide appropriate guidance to the urban rail transit management sector and help in maintaining the sustainability of urban rail transit operations as the mode of public transportation with the highest rate of use in most cities, which raises an important basis for improving the sustainability of urban development.

5.2. Discussion

Our research can be improved in the future in the following aspects:

1. In the simulation, the train logics were not created using the track library; only the arrival and departure of the trains are represented in the EVENT module in Anylogic 8.7.0, so the second-ride ratio could not be directly derived from the software and was instead directly assumed according to the field investigations, which may have caused some misalignments in the evaluation results. Similarly, due to the high punctuality of urban rail transit at present, there are few delays, so the average train delay time needs to be obtained from a lot of long-term statistics. Due to the limited time resources, in this paper, we also assumed the average train delay time directly according to the field investigations.
2. The subjectivity component included in the G1 method leads to results that may not be unique; therefore, in our future research, we will focus on addressing this issue by using quantitative methods to obtain objective weights for each influencing factor and reduce the influence of the subjectivity component.
3. The current transfer station improvement priorities proposed in Section 4.4 are based on assessment results, and it is hoped that more quantitative research on the priorities for improvements can be introduced in future studies using data combined with simulation to make these priorities for improvements more convincing.
4. The model developed in this paper has been verified for its feasibility using real scenarios and real data, as discussed in Section 4, and practical applications are also currently being carried out, which will be reflected in our future work.

Author Contributions: Conceptualization, X.Y. and J.C.; Methodology, X.Y. and J.C.; Software, X.Y.; Validation, X.Y.; Formal analysis, X.Y.; Investigation, X.Y. and Y.L.; Data curation, X.Y. and Y.L.; Writing—original draft, X.Y.; Writing—review & editing, J.C.; Visualization, X.Y. and Y.L.; Supervision, J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by China State Railway Group Co., Ltd. Science and technology research and development program grant number N2022X030.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the first author.

Acknowledgments: We would like to thank Yangyang Zhao of Chang'an University for providing us with preliminary guidance, and Lijie Yu of Chang'an University for providing us with example data and CAD drawings.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. G1 Method Importance Ranking Table: Round__(Translated Version)

1. For Level 1 factors

(1) Ranking the importance of the five level 1 factors

Level 1 factors include Rapidity before disturbance (U_1), Robustness (U_2), Redundancy (U_3), Resourcefulness (U_4), Rapidity after disturbance (U_5). Please rank the factors that affect the resilience of the transfer stations according to your understanding of their importance.

Rank	1	2	3	4	5
Index					

Notice:

Rapidity before disturbance indicates the rapidity of passenger movement within the station;

Robustness mainly refers to the resistance of the existing resources of the urban rail transit transfer system to disturbance, which is the basic capability of the system;

Redundancy refers to the disaster preparedness and capacity surplus of transfer facilities, which is related to the capacity of equipment and facilities;

Resourcefulness refers to the resource availability of the transfer station in the process of resistant disturbance and the recovery stage after disturbance, and can be expressed in terms of the travel options that can be dispatched by the entire transfer station at the same time;

Rapidity after disturbance indicates the rapidity of transfer evacuation after a disturbance;

(2) Judging the degree of importance ratio

Based on the importance ranking among the factors determined in the previous step, the importance is further quantified below. Suppose the ratio of importance is:

$$\omega_{k-1} = r_{k-1}\omega_k \tag{22}$$

where, r_k is called the tone operator. At present, the nine-level operator method is commonly used, as shown in the following table:

Table A1. Representation of tone operators.

r_k	Note
1.0	x_k,x_{k-1} are equally important
1.1	x_k,x_{k-1} is between equal importance and slightly important
1.2	x_k,x_{k-1} is slightly important
1.3	x_k,x_{k-1} is between slightly important and obviously important
1.4	x_k,x_{k-1} is obviously important
1.5	x_k,x_{k-1} is between obvious importance and strong importance
1.6	x_k,x_{k-1} is strongly important
1.7	x_k,x_{k-1} is between strongly important and extremely important
1.8	x_k,x_{k-1} is extremely important

Please give the importance ratio you have in mind based on the tone operator:

Importance ratio	Value
r_2	
r_3	
r_4	
r_5	

2. For Level 2 factors

(1) Ranking the importance of the two sub-factors of Rapidity before disturbance

Unit service time ($u_1^{(1)}$) of the servers and **average walking rate ($u_1^{(2)}$)** in the channel-type facilities are the two sub-factors of Rapidity before disturbance. Please rank the factors that affect Rapidity before disturbance according to your understanding of their importance.

Rank	1	2
Index		

Please give the importance ratio you have in mind based on the tone operator:

Importance ratio	Value
r_2	

(2) Ranking the importance of the four sub-factors of Robustness

Sub-factors of Robustness include: number of interweaving points of passengers ($\boldsymbol{u}_2^{(1)}$), second-ride ratio ($\boldsymbol{u}_2^{(2)}$), Average duration of station peak ($\boldsymbol{u}_2^{(3)}$), and average train peak delay ($\boldsymbol{u}_2^{(4)}$). Please rank each factor that affects transfer station robustness according to your understanding of their importance.

Rank	1	2	3	4
Index				

Please give the importance ratio you have in mind based on the tone operator:

Importance ratio	Value
r_2	
r_3	
r_4	

References

1. Mattsson, L.-G.; Jenelius, E. Vulnerability and resilience of transport systems—A discussion of recent research. *Transp. Res. Part A Policy Pract.* **2015**, *81*, 16–34. [CrossRef]
2. Holling, C.S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Evol. Syst.* **1973**, *4*, 1–23. [CrossRef]
3. Holling, C.S. *Engineering Resilience versus Ecological Resilience*; National Academies Press: Washington, DC, USA, 1996.
4. Murray-Tuite, P.M. A Comparison of Transportation Network Resilience under Simulated System Optimum and User Equilibrium Conditions. In Proceedings of the 2006 Winter Simulation Conference, Monterey, CA, USA, 3–6 December 2006; pp. 1398–1405.
5. Cats, O.; Jenelius, E. Dynamic Vulnerability Analysis of Public Transport Networks: Mitigation Effects of Real-Time Information. *Netw. Spat. Econ.* **2014**, *14*, 435–463. [CrossRef]
6. Amghar, R.; Jaber, S.; Moghaddam, S.M.H.M.; Bhouri, N.; Ameli, M. Resilience as a Service for Transportation Networks: Definition and Basic Concepts. *Transp. Res. Rec.* **2024**, *2678*, 177–189. [CrossRef]
7. Lu, Q.-C. Modeling network resilience of rail transit under operational incidents. *Transp. Res. Part A Policy Pract.* **2018**, *117*, 227–237. [CrossRef]
8. Li, M.; Wang, H.; Wang, H. Resilience Assessment and Optimization for Urban Rail Transit Networks: A Case Study of Beijing Subway Network. *IEEE Access* **2019**, *7*, 71221–71234. [CrossRef]
9. Bešinović, N. Resilience in railway transport systems: A literature review and research agenda. *Transp. Rev.* **2020**, *40*, 457–478. [CrossRef]
10. Fabella, V.M.; Szymczak, S. Resilience of Railway Transport to Four Types of Natural Hazards: An Analysis of Daily Train Volumes. *Infrastructures* **2021**, *6*, 174. [CrossRef]
11. Tang, J.; Xu, L.; Luo, C.; Ng, T.S.A. Multi-disruption resilience assessment of rail transit systems with optimized commuter flows. *Reliab. Eng. Syst. Saf.* **2021**, *214*, 107715. [CrossRef]
12. Watson, J.R.; Chatterjee, S.; Ganguly, A. Resilience of Urban Rail Transit Networks under Compound Natural and Opportunistic Failures. In Proceedings of the 2022 IEEE International Symposium on Technologies for Homeland Security (HST), Virtual, 14–15 November 2022; pp. 1–8.
13. Chen, J.; Liu, J.; Du, B.; Peng, Q.; Yin, Y. Resilience Assessment of an Urban Rail Transit Network Under Short-Term Operational Disturbances. *IEEE Trans. Intell. Transp. Syst.* **2022**, *23*, 24841–24853. [CrossRef]
14. Zhang, J.; Ren, G.; Song, J. Resilience-Based Restoration Sequence Optimization for Metro Networks: A Case Study in China. *J. Adv. Transp.* **2022**, *2022*, 8595356. [CrossRef]
15. Zheng, M.; Zuo, H.; Zhou, Z.; Bai, Y. Recovery Strategies for Urban Rail Transit Network Based on Comprehensive Resilience. *Sustainability* **2023**, *15*, 15018. [CrossRef]
16. Knoester, M.J.; Bešinović, N.; Afghari, A.P.; Goverde, R.M.P.; van Egmond, J. A data-driven approach for quantifying the resilience of railway networks. *Transp. Res. Part A Policy Pract.* **2024**, *179*, 103913. [CrossRef]
17. Jiao, L.; Zhu, Y.; Huo, X.; Wu, Y.; Zhang, Y. Resilience assessment of metro stations against rainstorm disaster based on cloud model: A case study in Chongqing, China. *Nat. Hazards* **2023**, *116*, 2311–2337. [CrossRef]
18. Bešinović, N.; Wang, Y.; Zhu, S.; Quaglietta, E.; Tang, T.; Goverde, R.M.P. A Matheuristic for the Integrated Disruption Management of Traffic, Passengers and Stations in Urban Railway Lines. *IEEE Trans. Intell. Transp. Syst.* **2022**, *23*, 10380–10394. [CrossRef]
19. Li, Z.; Yin, J.; Chai, S.; Tang, T.; Yang, L. Optimization of system resilience in urban rail systems: Train rescheduling considering congestions of stations. *Comput. Ind. Eng.* **2023**, *185*, 109657. [CrossRef]
20. Bruneau, M.; Reinhorn, A. Exploring the concept of seismic resilience for acute care facilities. *Earthq. Spectra* **2007**, *23*, 41–62. [CrossRef]

21. Wang, Y.L.; Liu, C.; Zhang, T.M.; Wang, L.; Wang, X.H.; Lu, Y.C.; Huo, H.J.; Wang, S. Research on investment value system of power grid emerging business based on index screening and G1-entropy weight method. In Proceedings of the 2nd International Conference on Applied Mathematics, Modelling, and Intelligent Computing (CAMMIC 2022), Kunming, China, 25–27 March 2022; pp. 41–46.
22. McPherson, S.; Reese, C.; Wendler, M.C. Methodology Update: Delphi Studies. *Nurs. Res.* **2018**, *67*, 404–410. [CrossRef]
23. Lam, W.H.K.; Cheung, C.Y. Pedestrian Speed/Flow Relationships for Walking Facilities in Hong Kong. *J. Transp. Eng.* **2000**, *126*, 343–349. [CrossRef]
24. Xin, Y.; Fu, L.; Saccomanno, F. Part 5: Capacity and Quality of Service: Assessing Transit Level of Service Along Travel Corridors: Case Study Using the Transit Capacity and Quality of Service Manual. *Transp. Res. Rec. J. Transp. Res. Board* **2005**, *1927*, 257–267. [CrossRef]
25. Davidich, M.; Geiss, F.; Mayer, H.G.; Pfaffinger, A.; Royer, C. Waiting zones for realistic modelling of pedestrian dynamics: A case study using two major German railway stations as examples. *Transp. Res. Part C Emerg. Technol.* **2013**, *37*, 210–222. [CrossRef]
26. Yang, M.S.; Zhao, Q.; Zhu, L.; Meng, H.N.; Chen, K.H.; Li, Z.J.; Hei, X.H. Semi-automatic representation of design code based on knowledge graph for automated compliance checking. *Comput. Ind.* **2023**, *150*, 103945. [CrossRef]