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Failure Mode and Effects Analysis of Accessibility in Frigid Zone Campus Buildings

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Abstract: With the progress of China's economy, there is an increasing focus on accessibility systems. Enhancements to accessibility infrastructure are being implemented in all types of structures, with a particular focus on educational institutions such as college campuses. This research was carried out to examine the campus accessibility system of Northeastern University's Nanhu and Hunnan Campuses in Shenyang City, China, using failure mode and effects analysis (FMEA) as a methodology and using incorporating fuzzy control, which overcomes the limitations of traditional FMEA. Fuzzy-FMEA integrates the fuzzy linguistic assessment to assist the analysis process, in contrast to standard analysis which mainly relies on subjective judgment. Through calculations, it is known that ramps, barrier-free toilets, and barrier-free entrances are the items with the highest failure modes. The construction of the campus accessible environment needs to prioritize solving the problems of these facilities. The research results also found that there is a lack of research specifications for accessible environments in China's cold regions, and universal specifications are not fully suitable. The accessibility of the new campus was improved and management was improved, reflecting the school's increased awareness of accessible environment construction in recent years. However, there are still many common problems in the old and new campuses, proving that they are not aware of the importance and urgency of improving these problems. In addition, the construction of barrier-free facilities in the administrative office buildings where management and faculty are located on both campuses is generally in good condition. The accessible design of dormitories and canteens commonly used by students is often ignored. Moreover, the rough detailing in many buildings prevents these facilities from being used properly. These are the challenges faced by the Northeastern University in building an accessible environment.

Keywords: accessible design; frigid zone campus; fuzzy control; fuzzy-FMEA; risk management

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1. Introduction

As China's economy progresses, the focus on accessibility as a crucial aspect of urban modernization is increasing. Nevertheless, as a result of China's inadequate infrastructure, numerous locations are incapable of fulfilling the requirements of people with disabilities [1]. In 2019, the Chinese government published a white paper, titled "Equality, Participation, Sharing: 70 Years of Protection of the Rights and Interests of Persons with Disabilities in New China". The paper highlights the integration of China's 85 million disabled individuals into the 13th Five-Year Plan and the allocation of CNY 41.669 billion towards the advancement of disability-related initiatives [2]. Chinese cities are enhancing the institutionalization of barrier-free facilities in accordance with national policies. In 2021, cities such as Beijing and Shanghai implemented enhanced municipal legislation to enhance the creation of accessible environments [3]. Assessing accessibility has become a significant concern for China in this particular setting.

A university in China is a multifunctional and extensive community that caters to various needs, including accommodation, education, research, commerce, and medical services. Although the university population is dominated by young and middle-aged students and the population structure is relatively simple, its population base is large and stable, and it also has a high demand for accessible environment. For example, there are many students who are injured in sports. The way the university's centralized accommodation is managed makes the accessibility of dormitories closely linked to student life. The university's teaching venues are mobile, and the unreasonable barrier-free circulation of teaching buildings prevents individuals with mobility impairments from reaching designated classrooms during short breaks [4]. The campus planning and construction design of campuses simultaneously reflect the national consciousness of spatial environment design concepts [5]. Therefore, the level of university campuses' accessibility can serve as a benchmark for assessing the accessibility of cities.

The Northeastern University comprises two distinct campuses: the Nanhu Campus, established in the 1950s, and the Hunnan Campus, which was finalized in 2019. Both the old and new campuses feature a diverse range of building types that effectively embody the principles of accessibility at different points in time. Simultaneously, the Northeastern University boasts a significant population of individuals with physical disabilities and houses an accessible research team dedicated to carrying out pertinent studies, reflecting the typical attribute of research. Furthermore, the frigid climate at Tohoku University's location necessitates specific accessibility requirements.

This research specifically examines the shortcomings of educational and residential structures' accessibility found on university campuses, with a particular emphasis on addressing the mobility and functional requirements of people with disabilities. The main goal of this study is to examine the accessibility standards of university facilities and spaces using legislative requirements and expert advice. The aim is to identify any shortcomings that may hinder the use of these facilities by individuals with disabilities. This study aimed to achieve four specific objectives: (1) examine and pinpoint accessibility concerns on both the old and new campuses of Northeastern University's campus space; (2) classify these concerns based on their level of severity; (3) analyze the most critical categories of issues and validate the experimental data; and (4) compare the data collected from the two campuses, analyze the problems posed by the current situation, and provide recommendations for improvement.

2. Literature Review

2.1. Accessibility

Accessibility involves the creation of an optimal setting that enables unrestricted and secure mobility and utilization for individuals of all ages, genders, and physical abilities. It aims to eliminate obstacles and promote maximum autonomy and respect.

The paper search process was conducted on 18 February 2024 in the Web of Science database (WOS). To compose the search string, we selected the main dimensions of our investigation. Using "accessible environment" and "accessible design" as search parameters, a total of 1947 related articles were retrieved, including engineering, chemistry, medical care, architecture, and other fields. In order to narrow the scope and be more precise, the academic fields were set as "Architecture" and "Environmental Science", and the publication time was set as 2008 to 2024. Finally, 177 results were obtained. We conducted out research based on these literature results.

International research on accessible environments began in 1990, when Hassan studied and proposed improvement measures for barrier-free transportation services for people with disabilities [6]. So far, accessibility research has shifted from demonstrating the necessity of accessible design and exploring design methods for urban accessible environments to the overall planning of accessibility, the improvement of concepts, and the humanized transformation of the design of various facilities. After sorting out the existing literature, it can be roughly summarized into three directions. Most of the literature found was based on urban or community accessibility research, which focuses on the impact of the level of accessible environment construction at the block scale on the accessibility of the population.

Secondly, there is research on the definition of accessible content, which focuses on how the needs for accessible facilities differ under different objective circumstances. Finally, there is research on barrier-free facilities, which evaluates various types and proposes improvement strategies.

In terms of community accessibility, Ann Heylighen et al. (2017) conducted a study on the inclusive design of the built environment. They identified the top ten issues that are related to this topic, demonstrating the wide range of ways in which humans interact with the built environment [5]. Chanwon Jo et al. (2021) conducted research on building construction and proposed a framework of informative standards to improve the creation of accessible environments in a sustainable manner [7]. Their focus was on combining diverse spatial qualities and using designs, including accessibility, to establish a systematic standard and methodology. Prandi et al. (2023) performed a lot of literature research studies and mapping analyses on proposing obstacle avoidance systems, which are devices and software applications that promote barrier-free pathfinding and navigation in indoor and outdoor environments [8].

In terms of defining accessible content, Matteo Zallio et al. (2022) used tracking surveys and interviews to record the challenges faced by people in the construction industry in their daily work. The objective conditions faced by accessible environment design in the construction industry were analyzed [9]. Jenna K Gillett-Swan et al. (2023) used educational and medical buildings as research objects to explore the decision-making role of children and teenagers in accessible design. It is proposed that the design of accessible environments should consider marginalized social groups, so that the degree of real users' needs for accessible environments can be clarified, and the content and standards of the design can be defined [10].

In terms of barrier-free facilities, Zahari et al. (2020) conducted a qualitative study at the micro level of accessibility. They used semi-structured interviews and follow-up interviews (accessibility audits) to assess the functionality of building facilities for people with disabilities. The study revealed that in certain situations, some of the building facilities were not suitable for people with disabilities [11]. The article points out that the entire society's awareness of accessibility must be improved to avoid incorrect design or incorrect use. For the design method of door locks for disabled access, etc., Tam et al. (2018) took Hong Kong as an example to evaluate existing handrail problems. Surveys and informal interviews were conducted with older adults, adults, and children to examine their needs. This study standardized and modified the concepts of handrail design and layout, and promoted universal design concepts to help create accessibility cities [12].

The extensive body of literature demonstrates that there is a growing social demand for an environment that is accessible to all individuals. From the macro level of urban environment construction to the micro level of facilities, accessible design plays an important role. At present, there are few research papers on the micro level of facilities in this field. Additionally, there is a significant lack of systematic research on the accessibility of different types of public buildings, such as the analysis of the accessibility system based on the campus.

2.2. Campus Accessibility

The current research on campus accessibility primarily focuses on architectural accessibility, specifically evaluating the accessibility of the research campus. Li Jiang et al. (2023) conducted a study that examined the correlation between college students' perception of accessibility to the internal transportation environment on campus and their satisfaction with commuting. They used structural equation modelling to analyze the data and found that perceptions of accessibility and positive emotions had a significant positive impact on commuting satisfaction [13].

Since there are not many qualitative and quantitative studies on campus accessibility, Osman et al. (2014) noted that there is not a uniform distribution of accessibility installations on university campuses and that the facilities that are there are not properly maintained by the university's administration. The facilities' state was evaluated from the viewpoint of individuals with disabilities using mean score analysis [14]. In the Hibatullah Stetieh et al. (2018) study, a number of disabled students and staff members were interviewed in order to examine the University of Jordan's Faculty of Engineering buildings in accordance with the Jordanian National Building Code and Requirements Specification for Buildings for People with Disabilities. The study discovered that numerous areas of the faculty are inaccessible and that many of the requirements specifications are not put into practice [15]. Machado et al. (2020) found significant issues with accessible spaces, tactile signage, bathroom fittings, and visual signage in this research school's accessibility system [16].

The current global trend in accessibility research, which is shifting from macro to micro levels, is creating an increasing demand for research on accessibility systems on college campuses. From the search results, "campus" and "accessibility facilities" appear to be associated with very few papers in the WOS database.

Around the world, university campuses frequently face the general issue of current accessibility constructions and facilities impeding, to some extent, the effective participation of the disabled community in regular activities and the ease of accessibility of the student community. Nevertheless, accurate assessments of each campus's accessibility systems and the management that follows, as well as research on the accessibility of campuses in unique environments, are lacking.

2.3. FMEA

Failure mode and effects analysis (FMEA) is an inductive analysis methodology that identifies fundamental faults or failures at the component level and assesses their impact on the system's normal operation. It is a systematic, documented, and iterative process.

FMEA techniques have been available since the late 1940s and have been used to predict and prevent potential failures in critical systems in the military and aerospace sectors. In the 1960s, FMEA became important in missile projects and space exploration programs. By the late 1970s, it started being applied in the automotive industry to enhance the quality and safety of products. During this time, the concept of the Risk Prioritization Number (RPN) was introduced, which assigns values to the likelihood, severity, and detectability of failures and prioritizes them in the product development lifecycle. In 2019, the concept of Action Prioritization (AP) was established to improve the assessment of risks and the prioritization of actions. This concept gradually replaced RPN. Currently, FMEA is used in various fields, including electronics, healthcare, and telecommunications. It is also integrated with modern techniques such as Fault Tree Analysis (FTA) and fuzzy control (fuzzy-FMEA) to enhance the efficiency of analysis and reporting.

Murphy et al. asserted that FMEA is appropriate for individuals who are interested but not professionally involved in analyzing or providing feedback on projects that aim to evaluate the potential risks of a structure [17]. Liu et al. described FMEA as a methodical process for identifying possible failure modes, along with their underlying causes and the impact they have on the performance of engineering management systems [18]. Thus, it is viable to employ FMEA to examine the accessible amenities in this research.

Oliveira et al. (2017) discovered that the ISO 31010:2009 standard provides a collection of 31 tools that are applicable to the process of risk management. The objective is to offer direction on systematic methodologies for identifying, analyzing, and assessing risks [19]. In their study on campus accessibility assessment, Machado et al. (2020) employed the ISO standard and the FMEA technique. They discovered that 80% of the accessibility system deficiencies in the schools examined were associated with accessible spaces, tactile signage, bathroom fittings, and visual signage [16]. However, most of the data sources in this article are obtained through questionnaires and interviews, which are highly subjective. Different research processes may lead to different results. In addition, the calculation only uses RPN grading, directly multiplying S, O, and D, and does not use the AP grading method. When the relationship between the three values of SOD is in a special state, the rating results of barrier-free facilities will not be accurate enough.

Generally, FMEA is widely used in many fields. But it is not accurate enough. The three SOD scores rely on subjectively generated ordinal numbers. The three are independent of each other and have no correlation. Therefore, later FMEA calculations usually introduce the AP classification method. At the same time, scorers have different criteria for judging scores, and there is great subjectivity and uncertainty in assessments. This does not allow for a fully justified conclusion to be drawn in an accessibility system assessment. Therefore, in order to improve the accuracy of research, the addition of fuzzy control can effectively solve this problem, namely fuzzy-FMEA. This approach reduces the subjectivity of scoring and helps more accurately reflect facility failure mode preferences.

2.4. Impact of Fuzzy-FMEA

Lotfi A. Zadeh [20] introduced the term "fuzzy logic system" during the 1960s. Fuzzy logic circumvents the use of binary dichotomous classifications, such as on/off and true/false. Instead, it is used to identify more varied and subtle categories, such as those that are large or very large. Fuzzy logic is a computational approach that involves using rule bases and fuzzy sets to derive results. It works by converting input values into fuzzy representations, evaluating them using a rule base, and then converting the output back into a crisp form. Therefore, the utilization of fuzzy theory in risk assessment yields a methodical evaluation that is qualitative and implemented in terms of linguistic variables.

Jéssica et al. (2018) investigated and developed a method for assessing the severity, occurrence, and detectability parameters of FMEA by combining fuzzy logic and product FMEA. Utilizing probability, severity, and detectability of failure modes, one can derive certainty from uncertainty in order to inform decision making, enhancing the precision and relevance of FMEA in relation to other research domains [21]. Ivančan et al. (2021) developed a novel FMEA ranking approach in their study. Four fuzzy logic systems were employed to compute the priority of failure modes and subsequently analyzed in a comparative manner [22].

According to the existing literature, fuzzy-FMEA, as an extended variant of FMEA, has been well evaluated in the manufacturing and medical fields. According to our understanding of fuzzy-FMEA, this method is feasible and effective for research in the field of accessibility. In particular, this method is able to balance the bias of expert panels on different semantic understandings. This can alleviate the uncertainty and complexity in assessing accessibility and make the results more accurate.

3. Materials and Methods

3.1. Characteristics of the Study Case

The Northeastern University is a public university situated in a frigid region of China. It has a total enrollment of 28,000 students and professors. Based on the data from Northeastern University's campus hospital in 2023, there are a total of 127 individuals with physical disabilities and 263 individuals who have sustained physical injuries at the college. Furthermore, the university founded the Center for Accessibility Studies in 2017. The team comprises professionals from several colleges, including architects, engineers, structural engineers, safety engineers, and doctors. This research examines the accessible systems of 41 university buildings with the help of the Center for Accessibility Research. The goal is to enhance the ease of movement and safety of individuals with disabilities in campus buildings. To accomplish the research objectives, the tools and procedures employed are illustrated in Figure 1.

3.2. Interviews and Questionnaires

Before commencing the survey, we performed an unstructured interview with the staff at the Center for Accessibility Research. The purpose was to compile a comprehensive list of accessibility characteristics in buildings that may hinder their usage by individuals with disabilities. Following the pilot test, the data were meticulously reviewed with the Chinese Accessibility Design Code on an individual basis to enhance the tables' content. Furthermore, a total of 50 individuals with disabilities, who have resided on the school premises for a duration exceeding two years, were interviewed to record and document any elements inside the campus that impede or hinder mobility for individuals with disabilities. While performing the field investigation, we noticed various failure modes of these items, traced the likely causes of their failure, and forecasted the impacts and consequences. Following this, deliberations took place with the Center for Accessibility Research to narrow down the facilities for this study. The failure modes and potential reasons of risk for each item were then addressed and mutually agreed upon, as seen in Table 1.

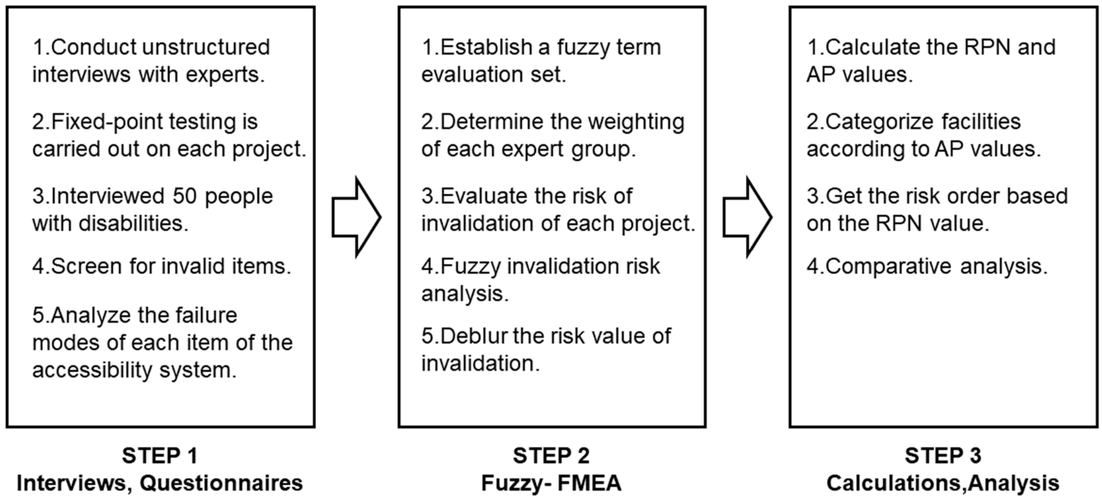

Figure 1. Research flowcharts.

Table 1. Fuzzy-FMEA: HSE risk forewarning indicators and invalidation mode analysis.

Number	Type of Risk	Forewarning Indicators	Reason for Invalidation	Major Invalidation Consequences
Item 1	Ramp	Quantity	No ramps	Obstruction of access
Item 2	Ramp	Scales	Irrational	Increased risk of accidents
Item 3	Ramp	Platform scale	Irrational	Affects normal use
Item 4	Ramp	Snowpack	The snow is icing	Risk of falling and frostbite
Item 5	Handrails for ramps	Height	Irrational	Obstruction of access
Item 6	Handrails for ramps	Temperature	Cold	Frostbite
Item 7	Handrails for ramps	Continuity	Discontinuous	Risk of falling
Item 8	Accessible entrances	Quantity	No accessible entrances	Obstruction of access
Item 9	Accessible entrances	Distance	Irrational	Obstruction of access
Item 10	Accessible entrances	Accessibility	Not easy to pass	Risk of falling
Item 11	Accessible entrances	Platform size	Irrational	Wheelchairs cannot be steered
Item 12	Accessible entrances	Curtains and doors	Tough to pass	Obstruction of access
Item 13	Accessible entrances	Canopy	No canopy	Rain and slippery roads
Item 14	Accessible entrances	window	No windows to watch	Unable to get to intended place after the door
Item 15	Accessible entrances	Doorknob	Cold	frostbite

Table 1. *Cont.*

Number	Type of Risk	Forewarning Indicators	Reason for Invalidation	Major Invalidation Consequences
Item 16	Accessible entrances	Door bucket	Short spacing	Wheelchairs cannot be steered
Item 17	Accessible entrances	Antifreeze treatment	No antifreeze treatment	Frostbite
Item 18	Classroom doors	Convenience	Threshold and no ramp	Wheelchair accessible
Item 19	Classroom doors	Windows	No windows	Unable to get to intended place after the door
Item 20	Elevator	Quantity	No elevator	Impassable
Item 21	Elevator	barrier-free elevators	Deficiency	Obstruction of access
Item 22	Elevator	Door opening time	Short	Obstruction of access
Item 23	Elevator	Handrail	Irrational	Risk of falling
Item 24	Elevator	Size	Irrational	Wheelchairs cannot be steered
Item 25	Staircase	Handrail	Irrational	Risk of falling
Item 26	Staircase	Size	Irrational	Obstruction of access
Item 27	Accessible toilet	Quantity	No toilet	Not available
Item 28	Accessible toilet	Handrail	Irrational	Risk of falling
Item 29	Accessible toilet	Size	Irrational	Wheelchairs cannot be steered
Item 30	Accessible toilet	Distribution	Uneven distribution	Not available
Item31	Accessible toilet	Facility's size	Irrational	Inconvenience
Item 32	Corridor	Width	Narrow	Wheelchairs cannot be steered
Item 33	Accessibility signage	Quantity	No signage	Time-consuming search

3.3. Fuzzy-FMEA

The principle of failure mode and effects analysis (FMEA) is to score the severity (S), occurrence (O), and detection (D) of the failure and accordingly determine the risk priority number (RPN) and action priority of the facility—level (AP) for evaluation. However, there are shortcomings in practical applications, such as neglecting fuzzy language evaluation, not considering the weight of risk factors, and over-reliance on the subjective judgment of experts. In order to solve these problems, this study uses fuzzy language in the evaluation process, which can more accurately and objectively express the scoring indicators of facility severity, occurrence, and detection.

Initially, we assessed the research objectives by examining the studied facilities through interviews and questionnaires. Subsequently, the expert team conducted a failure analysis for each item using fuzzy language. The research team then calculated the overall evaluation of the fuzzy failure risk analysis by considering the weights assigned to each factor.

Human thinking and speech can be imprecise, leading to the usage of fuzzy language in evaluating service success. This includes phrases like "should", "seemingly", and "very prominent." Thus, in this work, the variables indicator severity (S), occurrence (O), and detection (D) are utilized as fuzzy linguistic variables to form a set of fuzzy linguistic terms. The evaluation of each variable involved the use of five evaluation phrases, and the score for each evaluation indicator was measured on a scale ranging from 0 to 10 [23]. In previous studies, fuzzy linguistic word sets were statistically characterized using triangular fuzzy numbers [24]. Suppose there are m experts and the weight of the jth expert is $a_j(j = 1, 2, \ldots, m)$. The evaluation of the risk of item failure by this expert (A_j) is represented by a triangular fuzzy number $\widetilde{A}_j = (L_j, M_j, U_j)$, where L represents the lower term value, M represents the mid bound, and U represents the upper bound, as shown in Equation (1).

$$\begin{cases} L = \sum_{j=0}^{m} a_j L_j \\ M = \sum_{j=0}^{m} a_j M_j \\ U = \sum_{j=0}^{m} a_j U_j \end{cases} \sum_{j=1}^{m} a_j = 1, a_j \in (0,1) \tag{1}$$

Table 2 displays the completed collection of item failures using a fuzzy ensemble. Given the triangular fuzzy number $\widetilde{A} = (L, M, U)$, the fuzzy number affiliation function is discretized according to Equation (2). The curve representing its affiliation function is displayed in Figure 2.

$$u_{\widetilde{A}}(x) = \begin{Bmatrix} \frac{x-L}{M-L} & L \le x \le M \\ \frac{U-x}{U-M} & M \le x \le U \\ 0 & Other \end{Bmatrix} \tag{2}$$

Table 2. Fuzzy term set.

Fuzzy Term	Severity (S)	Occurrence (O)	Detection (D)	Fuzzy Number
Very low (R)	Barely noticeable	Unlikely	High	(0,0,1)
Low (L)	Slight impact	Very little	Moderate	(0,1.5,3)
Middle (M)	Middle impact	Little	Little	(2.5,4.5,6.5)
High (H)	Serious impact	High	Very Little	(6,7.5,9)
Very high (VH)	Very serious impact	Alarming	Unlikely	(8.5,10,10)

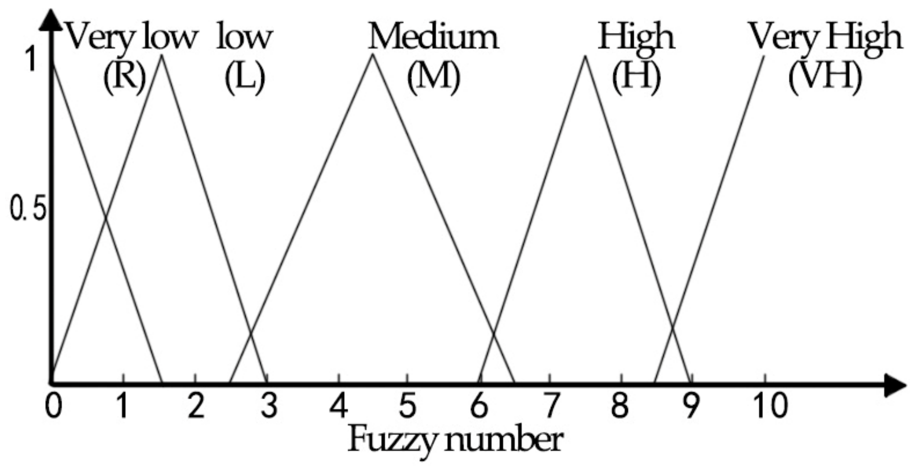

Figure 2. Membership function curve of fuzzy language function.

For this research, 20 experts from the Center for Accessibility Research were invited to form an assessment macro-cluster consisting of 5 groups: ergonomists (4), structural engineers (4), engineers (4), architects (4), and physicians (4). After three discussions, the expert group decided to give each group of experts the weights for facility failure severity (S), occurrence (O), and detection (D) based on the differences in knowledge areas reflected in the five degrees, as shown in Table 3. During this study, severity (S) denotes the degree to which people suffer when barrier-free facilities fail. It assesses human health, so ergonomics and doctors have greater importance. The degree of occurrence (O) indicates the frequency of hazard occurrence when barrier-free facilities fail. It assesses building space, so architects and engineers have greater importance. Detection degree (D) indicates the possibility of discovering the failure of a barrier-free facility before use, mainly manifested in structural deformation, so the structural engineer has greater importance.

Table 3. Expert group weight.

Type of Expert	Severity (S)	Occurrence (O)	Detection (D)
Ergonomist	0.32	0.14	0.13
Structural Engineer	0.14	0.17	0.30
Engineer	0.12	0.21	0.19
Architect	0.20	0.31	0.23
Doctor	0.22	0.17	0.15

In order to synthesize the opinions of 20 experts, this research weights and sums the failure risk factors assessed by each expert, as shown in Equations (3)–(5). S_i, O_i, and D_i represent the fuzzy values for the severity, occurrence, and detection of failure modes in the ith item, respectively. a_{Sj}, a_{Oj}, and a_{Dj} represent the weight assigned by the jth expert to assess the severity, occurrence, and detection of failure modes in the i item, respectively. The fuzzy values S_{ij}, O_{ij}, and D_{ij} represent the evaluation levels of the jth expert for the severity, occurrence, and detection of the ith item, respectively. The equation includes three fuzzy numbers in each fuzzy level: S_{ijL}, O_{ijL}, and D_{ijL}. These represent the minimum fuzzy numbers obtained when the jth expert evaluates the severity, occurrence, and detection levels of the failure mode of the ith item, respectively. Similarly, S_{ijM}, O_{ijM}, and D_{ijM} represent the intermediate fuzzy numbers obtained when the jth expert evaluates the severity, occurrence, and detection levels of the failure mode of the ith item. Lastly, S_{ijU}, O_{ijU}, and D_{ijU} represent the maximum fuzzy numbers obtained when the jth expert evaluates the severity, occurrence, and detection levels of the failure mode of the ith item.

$$S_i = \sum_{j=1}^{m} a_{Sj} S_{ij} = \left(\sum_{j=1}^{m} a_{Sj} S_{ijL}, \sum_{j=1}^{m} a_{Sj} S_{ijM}, \sum_{j=1}^{m} a_{Sj} S_{ijU} \right) \quad (3)$$

$$O_i = \sum_{j=1}^{m} a_{Oj} O_{ij} = \left(\sum_{j=1}^{m} a_{Oj} O_{ijL}, \sum_{j=1}^{m} a_{Oj} O_{ijM}, \sum_{j=1}^{m} a_{Oj} O_{ijU} \right) \quad (4)$$

$$D_i = \sum_{j=1}^{m} a_{Dj} D_{ij} = \left(\sum_{j=1}^{m} a_{Dj} D_{ijL}, \sum_{j=1}^{m} a_{Dj} D_{ijM}, \sum_{j=1}^{m} a_{Dj} D_{ijU} \right) \quad (5)$$

To provide a quantitative comparison of the failure risks of different items, it is necessary to defuzzify the assessment results. The widely employed center of gravity approach calculates the failure risk value by determining the center of gravity value of the area bounded by the curve of the affiliation function and the horizontal coordinate [25]. The value $x(\tilde{A})$ represents the risk of failure of the defuzzified service contact point, and it is calculated using Equation (6).

$$x(\tilde{A}) = \frac{\int_L^U x \mu_{\tilde{A}}(x) dx}{\int_L^U \mu_{\tilde{A}}(x) dx} \quad (6)$$

The defuzzification process of triangular fuzzy integers S_i, O_i, and D_i, which represents the severity, occurrence, and detection of failure modes of an item, can be expressed as Equations (7)–(9), correspondingly, based on Equation (6). DS_i, DO_i, and DD_i represent the quantified values of severity, occurrence, and detection of the failure risk for the ith item, which are calculated by the fuzzification process. S_{iL}, O_{iL}, and D_{iL} represent the lowest fuzzy numbers derived from evaluating the severity, occurrence, and detection levels of failure modes in the ith item. Similarly, S_{iM}, O_{iM}, and D_{iM} represent the intermediate fuzzy numbers obtained when evaluating the severity, occurrence, and detection levels of the failure mode of the ith item, respectively. S_{iU}, O_{iU}, and D_{iU} represent the maximum fuzzy numbers obtained when evaluating the severity, occurrence, and detection levels of the failure mode of the ith item, respectively.

$$DS_i = \frac{1}{3}[(S_{iU} - S_{iL}) + (S_{iM} - S_{iL})] + S_{iL} \quad (7)$$

$$DO_i = \frac{1}{3}[(O_{iU} - O_{iL}) + (O_{iM} - O_{iL})] + O_{iL} \quad (8)$$

$$DD_i = \frac{1}{3}[(D_{iU} - D_{iL}) + (D_{iM} - D_{iL})] + D_{iL} \quad (9)$$

After conducting a failure risk evaluation of the item, experts performed fuzzification and defuzzification to generate the item failure risk value R (known as the RPN) [26]. The calculating process is illustrated in Equation (10).

$$R = DS_i \cdot DO_i \cdot DD_i \quad (10)$$

In the traditional definition of FMEA, the higher the RPN value, the greater the risk of failure [27]. Therefore, the RPN value we calculated can represent the degree of failure risk of on-campus barrier-free facilities. Nevertheless, FMEA investigation results often ignore failure types with high severity, low occurrence, and high detection, leading to the negligence of some failure modes. In order to obtain more accurate conclusions, this study also compared the DFMEA part of the fifth edition of the FMEA manual (AIAG and VDA) to obtain AP-level binding analysis. The higher the AP level, the higher the priority of risk management [28].

4. Results

4.1. Data Overview

This research assessed the fuzzy grades of severity, occurrence, and detection for each facility failure mode using the scoring criteria outlined in Table 2. The results of this evaluation can be found in Table 4. The severity, occurrence, and detection degrees of the facilities were fuzzified, in conjunction with the expert weight matrix presented in Table 3. The sequential calculation of the severity, occurrence, and detection of fuzzy numbers is performed according to Equations (3)–(5), as displayed in Table 5.

4.2. Priority Ranking for Accessibility

Based on the information provided in Table 5, using Equations (7)–(9), the final SOD value for each item was determined. Additionally, using Equation (10), the failure risk value R was calculated. Subsequently, a ranking and an AP class evaluation were conducted, and the results are displayed in Table 6.

The AP level assessment included a total of 33 items, which were ranked in order of priority from highest to lowest as H, M, and L. There were three items classified as the most severe level of H, nine items classified as medium priority level of M, and twenty-one items classified as the lowest level of L.

The AP ratings for H are as follows: I4—ramp snow; I6—ramp handrail cold temperature; and I30—uneven distribution of accessible toilets.

The AP ratings for M are as follows: I8—some buildings lack accessible entrances; I10—some accessible entrances are too narrow; I13—some accessible entrances lack canopies; I15—handles in accessible entrances have low temperature; I19—classroom doors lack windows; I21—some buildings lack accessible elevators; I22—elevator door opening time is too short; I28—accessible toilets have unreasonable handrail scales; and I31—accessible toilets have unreasonable spatial scales.

An AP grade of L was assigned to each of the remaining items.

The R values of all the items can be sorted, revealing that the highest value is 402 and the lowest value is 37, indicating a significant range. Out of the items mentioned, there are a total of 8 that have a score of 149 or higher. These items, listed in descending order, are I6, I30, I28, I4, I31, I29, I15, and I22. Except for I29, all of these items have grades of H or M. By integrating the AP grade with the R value ranking, the assessment of item prioritization becomes more precise, and certain items will be further examined in relation to the statute.

Table 4. SOD fuzzy level results of items.

Item	Ergonomist				Structural Engineer				Engineer				Architect				Doctor			
	ER1	**ER2**	**ER3**	**ER4**	**S1**	**S2**	**S3**	**S4**	**EN1**	**EN2**	**EN3**	**EN4**	**A1**	**A2**	**A3**	**A4**	**D1**	**D2**	**D3**	**D4**
I1	(M,VH,L)	(H,H,L)	(M,L,L)	(M,M,L)	(L,M,M)	(L,H,M)	(M,M,L)	(L,M,L)	(L,L,L)	(M,L,M)	(L,M,L)	(H,L,M)	(H,H,VH)	(H,H,M)	(H,L,L)	(M,M,M)	(M,M,L)	(VH,M,M)	(M,L,H)	(L,L,L)
I2	(M,L,H)	(H,M,H)	(M,M,H)	(M,M,M)	(M,L,VH)	(M,H,H)	(M,L,M)	(L,L,L)	(M,L,L)	(L,M,L)	(L,L,L)	(H,M,M)	(L,L,M)	(M,L,L)	(L,M,M)	(M,L,M)	(L,L,M)	(H,H,VH)	(L,L,M)	(M,L,M)
I3	(M,H,H)	(H,H,H)	(H,M,M)	(H,M,M)	(L,M,L)	(H,H,L)	(L,M,M)	(M,M,M)	(M,M,L)	(M,M,L)	(M,M,L)	(H,M,H)	(H,H,M)	(M,H,M)	(M,M,M)	(H,M,M)	(M,M,M)	(M,M,H)	(M,M,L)	(M,M,L)
I4	(VH,VH,L)	(H,M,L)	(VH,VH,L)	(H,VH,L)	(M,VH,L)	(VH,H,L)	(H,VH,L)	(H,H,M)	(H,H,L)	(VH,VH,L)	(VH,H,L)	(M,L,H)	(VH,VH,L)	(H,VH,L)	(H,H,L)	(H,M,L)	(M,M,M)	(M,M,H)	(VH,M,M)	(H,M,L)
I5	(L,L,H)	(M,M,H)	(M,L,H)	(M,H,H)	(L,M,M)	(L,M,M)	(M,M,M)	(M,H,M)	(L,L,H)	(H,M,L)	(H,M,L)	(L,M,L)	(H,H,M)	(M,H,M)	(M,H,M)	(H,M,M)	(R,R,L)	(H,M,M)	(M,L,L)	(L,L,M)
I6	(L,H,M)	(M,M,L)	(VH,H,L)	(M,M,M)	(L,M,L)	(M,L,M)	(M,M,L)	(L,H,M)	(H,M,H)	(M,M,L)	(L,L,VH)	(L,H,H)	(VH,VH,M)	(M,H,H)	(H,VH,VH)	(M,M,M)	(H,M,M)	(M,L,M)	(M,M,M)	(H,H,M)
I7	(L,M,L)	(L,M,M)	(M,L,M)	(M,M,H)	(L,M,L)	(L,L,H)	(L,M,L)	(M,M,M)	(L,H,L)	(L,L,L)	(M,M,M)	(L,L,M)	(H,H,M)	(L,M,L)	(H,H,L)	(H,H,M)	(L,L,R)	(M,M,M)	(M,L,L)	(L,L,L)
I8	(M,M,M)	(M,M,M)	(H,L,L)	(M,H,M)	(M,M,L)	(H,H,L)	(L,M,L)	(L,L,L)	(L,L,M)	(M,L,M)	(VH,L,VH)	(M,M,H)	(M,M,L)	(H,M,M)	(H,L,L)	(M,L,L)	(M,M,M)	(M,H,H)	(L,L,L)	(L,M,L)
I9	(L,M,L)	(H,M,M)	(M,M,M)	(L,H,VH)	(L,L,L)	(L,M,L)	(M,L,L)	(M,M,M)	(L,L,M)	(L,L,L)	(L,L,VH)	(L,L,H)	(M,L,M)	(L,M,L)	(L,L,L)	(M,M,M)	(M,M,M)	(H,H,H)	(M,M,M)	(M,L,M)
I10	(M,H,VH)	(H,H,H)	(VH,H,H)	(M,H,VH)	(M,M,M)	(HM,M)	(M,M,M)	(L,M,M)	(M,L,M)	(L,M,L)	(H,M,L)	(M,M,M)	(M,M,L)	(M,M,M)	(L,VH,L)	(H,VH,L)	(M,M,M)	(H,H,H)	(M,M,L)	(M,M,M)
I11	(L,L,L)	(L,L,M)	(H,M,M)	(M,H,H)	(L,L,L)	(M,M,M)	(L,L,L)	(M,L,L)	(M,L,L)	(M,L,L)	(H,M,L)	(L,M,H)	(L,L,L)	(M,L,M)	(H,VH,M)	(M,M,L)	(R,R,R)	(VH,H,VH)	(L,L,M)	(L,L,M)
I12	(L,H,L)	(L,M,L)	(VH,M,L)	(M,H,VH)	(L,M,L)	(L,M,H)	(L,M,L)	(L,M,L)	(L,L,M)	(M,L,M)	(VH,L,L)	(R,R,VH)	(M,M,L)	(M,L,L)	(M,VH,L)	(L,M,L)	(M,L,M)	(M,M,H)	(L,M,M)	(M,M,L)
I13	(L,H,M)	(H,M,L)	(M,L,L)	(L,H,VH)	(M,M,M)	(L,M,H)	(H,L,L)	(M,M,L)	(M,M,L)	(L,M,L)	(M,L,M)	(L,H,H)	(M,H,M)	(M,VH,M)	(M,VH,L)	(L,L,L)	(M,M,H)	(H,VH,H)	(L,L,L)	(H,M,L)
I14	(L,L,L)	(L,M,L)	(VH,M,L)	(H,M,VH)	(M,L,M)	(H,M,H)	(L,M,L)	(L,M,L)	(L,M,L)	(H,L,L)	(VH,L,L)	(L,H,H)	(L,M,L)	(M,H,VH)	(H,M,L)	(L,L,M)	(L,R,R)	(H,H,H)	(H,L,H)	(L,M,L)
I15	(L,M,H)	(M,M,M)	(VH,H,L)	(L,M,M)	(L,M,M)	(L,L,M)	(L,M,L)	(L,L,M)	(M,L,H)	(L,H,L)	(L,L,VH)	(M,M,H)	(H,H,M)	(H,H,M)	(M,VH,VH)	(M,L,L)	(M,M,H)	(H,H,VH)	(L,L,H)	(L,L,M)
I16	(L,L,L)	(L,L,H)	(VH,M,M)	(H,H,VH)	(L,L,L)	(L,H,M)	(M,H,L)	(H,L,L)	(L,L,L)	(L,L,M)	(L,L,L)	(R,R,M)	(L,L,L)	(L,H,L)	(M,VH,H)	(M,M,L)	(L,L,R)	(VH,H,H)	(L,L,M)	(L,L,M)
I17	(L,H,L)	(M,H,M)	(H,M,L)	(M,M,M)	(L,H,H)	(L,L,M)	(M,M,L)	(L,M,M)	(H,M,L)	(L,VH,M)	(M,M,L)	(L,M,H)	(M,L,M)	(L,M,M)	(M,M,L)	(M,L,L)	(M,M,M)	(VH,VH,VH)	(M,M,L)	(H,H,M)
I18	(M,VH,L)	(H,H,M)	(H,H,L)	(L,H,M)	(H,M,H)	(M,H,H)	(M,M,L)	(M,M,M)	(L,L,L)	(L,M,L)	(L,L,H)	(H,M,H)	(H,H,M)	(M,L,L)	(L,H,L)	(M,L,L)	(M,M,M)	(H,H,H)	(L,M,M)	(M,M,L)
I19	(L,L,L)	(L,M,L)	(M,M,L)	(H,M,VH)	(L,L,L)	(M,M,H)	(M,L,L)	(L,H,L)	(L,L,M)	(M,L,L)	(VH,L,L)	(R,R,R)	(L,L,L)	(H,H,M)	(M,M,M)	(M,L,L)	(L,L,R)	(VH,VH,VH)	(L,M,M)	(L,H,L)
I20	(L,L,L)	(L,M,L)	(M,HV,L)	(M,M,H)	(L,M,L)	(M,M,M)	(M,M,H)	(M,L,L)	(M,L,L)	(M,L,L)	(M,L,M)	(R,R,R)	(L,L,L)	(M,H,H)	(L,H,L)	(M,L,L)	(L,R,R)	(M,H,H)	(L,L,H)	(H,L,L)
I21	(L,L,VH)	(M,M,M)	(M,VH,M)	(L,L,VH)	(M,H,L)	(M,M,H)	(M,H,H)	(M,M,L)	(M,M,M)	(M,H,H)	(M,L,H)	(M,M,L)	(M,H,M)	(M,M,VH)	(L,H,H)	(M,M,L)	(M,L,M)	(M,H,M)	(M,L,M)	(M,M,M)
I22	(M,H,H)	(M,H,M)	(M,VH,M)	(L,M,VH)	(H,M,H)	(L,H,M)	(M,H,M)	(L,M,H)	(L,L,M)	(H,M,L)	(M,L,L)	(L,M,L)	(M,M,L)	(M,M,VH)	(M,H,M)	(M,L,L)	(L,R,R)	(M,H,M)	(H,L,M)	(M,M,M)
I23	(M,L,L)	(M,M,H)	(M,VH,M)	(M,M,VH)	(VH,H,M)	(L,L,VH)	(M,M,L)	(M,M,L)	(H,H,M)	(M,M,L)	(M,L,L)	(L,L,H)	(M,H,M)	(M,M,L)	(M,M,H)	(M,M,L)	(M,L,M)	(M,M,M)	(L,L,M)	(M,H,M)
I24	(L,L,VH)	(M,M,H)	(M,VH,H)	(L,M,VH)	(M,M,H)	(L,L,VH)	(M,L,M)	(M,L,L)	(L,H,L)	(L,M,L)	(L,M,L)	(R,R,H)	(L,L,L)	(M,H,M)	(M,H,M)	(M,L,L)	(L,L,R)	(H,H,VH)	(M,M,H)	(L,L,M)
I25	(H,L,VH)	(H,M,H)	(M,H,M)	(M,M,H)	(M,L,M)	(LLH)	(M,L,L)	(M,M,M)	(H,L,L)	(M,L,L)	(H,H,M)	(L,M,M)	(M,L,L)	(M,M,H)	(M,H,H)	(M,M,L)	(M,M,M)	(M,H,VH)	(L,M,H)	(L,M,M)
I26	(L,L,VH)	(H,M,H)	(VH,H,H)	(M,M,H)	(M,M,M)	(M,M,H)	(M,M,M)	(M,M,M)	(LLH)	(H,M,L)	(L,M,M)	(L,L,H)	(M,M,L)	(M,M,H)	(M,H,H)	(M,M,L)	(M,M,H)	(M,M,M)	(M,M,H)	(M,M,H)
I27	(H,VH,M)	(H,H,M)	(H,VH,M)	(H,M,VH)	(L,L,M)	(L,M,M)	(M,M,M)	(M,L,M)	(M,H,H)	(M,H,VH)	(H,M,VH)	(M,L,L)	(M,H,M)	(H,M,M)	(H,H,L)	(M,M,M)	(M,L,M)	(M,H,H)	(L,L,M)	(L,M,H)
I28	(M,L,VH)	(H,M,H)	(H,VH,M)	(M,M,VH)	(M,H,M)	(M,M,M)	(H,H,M)	(LLM)	(M,L,M)	(M,L,L)	(M,L,VH)	(L,M,M)	(H,H,M)	(H,M,L)	(H,H,H)	(M,L,M)	(M,M,M)	(VH,H,H)	(M,LM)	(M,H,VH)
I29	(H,VH,VH)	(H,M,H)	(VH,VH,L)	(M,M,VH)	(M,H,M)	(L,L,H)	(M,M,L)	(L,M,M)	(M,H,L)	(M,L,L)	(L,M,L)	(L,L,H)	(H,H,M)	(H,M,L)	(M,H,H)	(M,M,M)	(M,M,M)	(H,H,H)	(M,M,M)	(M,H,VH)
I30	(M,H,H)	(H,H,M)	(LLM)	(H,M,VH)	(L,L,VH)	(L,VH,L)	(M,M,L)	(M,M,M)	(M,H,H)	(M,L,VH)	(H,H,M)	(L,L,M)	(VH,VH,H)	(M,M,VH)	(M,M,M)	(H,L,M)	(M,M,H)	(H,M,M)	(L,M,VH)	(M,H,VH)
I31	(M,H,H)	(H,M,H)	(M,M,M)	(M,M,VH)	(H,M,H)	(L,H,H)	(M,H,L)	(L,L,M)	(M,M,H)	(M,L,L)	(H,M,M)	(L,L,H)	(H,H,M)	(M,M,M)	(H,H,H)	(M,L,L)	(M,M,M)	(H,M,M)	(H,L,M)	(M,M,H)
I32	(L,L,H)	(M,M,M)	(VH,VH,L)	(M,M,M)	(L,LM)	(L,L,H)	(LLL)	(L,L,M)	(M,L,L)	(LLL)	(VH,L,H)	(M,H,L)	(LLL)	(L,M,L)	(M,H,M)	(M,M,L)	(M,M,M)	(M,H,H)	(L,L,M)	(L,L,M)
I33	(L,M,M)	(M,H,M)	(VH,VH,M)	(LH,VH)	(L,M,H)	(L,L,H)	(LLL)	(M,M,L)	(LLM)	(L,M,H)	(L,L,M)	(L,L,L)	(M,M,M)	(M,M,L)	(M,H,M)	(M,M,M)	(M,L,M)	(M,M,M)	(M,LM)	(M,M,M)

Table 5. Evaluation results of SOD.

Item	Severity (S)	Occurrence (O)	Detection (D)
I1	(3.705, 5.425, 6.950)	(3.414, 5.113, 6.556)	(3.351, 4.973, 6.144)
I2	(2.228, 3.975, 5.723)	(1.363, 3.000, 4.638)	(4.510, 6.165, 7.280)
I3	(3.353, 5.145, 6.938)	(3.366, 5.243, 7.119)	(2.236, 3.998, 5.759)
I4	(7.463, 8.988, 9.530)	(6.788, 8.330, 9.033)	(1.534, 3.063, 4.396)
I5	(2.088, 3.623, 5.238)	(2.760, 4.463, 6.200)	(2.673, 4.470, 6.268)
I6	(6.240, 7.870, 8.810)	(5.454, 7.093, 8.476)	(6.105, 7.765, 8.690)
I7	(1.505, 3.180, 4.855)	(2.305, 4.050, 5.795)	(1.595, 3.251, 4.940)
I8	(5.503, 7.145, 8.128)	(2.049, 3.773, 5.496)	(2.360, 3.970, 5.298)
I9	(1.973, 3.705, 5.438)	(1.559, 3.278, 4.996)	(3.079, 4.769, 6.118)
I10	(4.015, 5.590, 6.835)	(4.106, 5.893, 7.424)	(2.633, 4.365, 5.873)
I11	(4.153, 5.795, 6.958)	(2.473, 4.033, 5.373)	(2.321, 3.963, 5.409)
I12	(3.753, 5.425, 6.618)	(3.205, 4.876, 6.345)	(2.636, 4.169, 5.360)
I13	(2.590, 4.290, 5.990)	(4.410, 6.100, 7.325)	(3.076, 4.819, 6.336)
I14	(4.573, 6.115, 7.148)	(2.111, 3.825, 5.574)	(4.989, 6.469, 7.306)
I15	(3.295, 4.900, 6.175)	(3.150, 4.835, 6.265)	(5.473, 7.096, 8.004)
I16	(5.190, 6.705, 7.440)	(2.946, 4.389, 5.629)	(2.464, 4.024, 5.391)
I17	(3.968, 5.615, 6.783)	(3.818, 5.559, 7.011)	(2.704, 4.398, 5.896)
I18	(2.918, 4.635, 6.353)	(3.418, 5.139, 6.796)	(2.136, 3.773, 5.409)
I19	(5.093, 6.755, 7.788)	(2.529, 4.074, 5.461)	(3.219, 4.746, 5.901)
I20	(1.730, 3.435, 5.170)	(1.875, 3.403, 4.954)	(1.673, 3.105, 4.618)
I21	(2.138, 4.065, 5.993)	(3.383, 5.094, 6.741)	(5.529, 7.118, 8.031)
I22	(2.900, 4.590, 6.280)	(3.323, 4.981, 6.611)	(5.165, 6.746, 7.685)
I23	(3.530, 5.360, 6.890)	(2.744, 4.471, 6.135)	(4.596, 6.223, 7.279)
I24	(1.593, 3.270, 4.978)	(2.153, 3.725, 5.286)	(4.995, 6.570, 7.380)
I25	(2.495, 4.290, 6.085)	(2.048, 3.750, 5.453)	(4.150, 5.755, 6.940)
I26	(3.700, 5.530, 7.030)	(2.429, 4.313, 6.196)	(4.306, 5.933, 7.334)
I27	(2.970, 4.680, 6.390)	(3.253, 5.938, 6.495)	(4.580, 6.340, 7.590)
I28	(4.748, 6.455, 8.043)	(5.505, 7.070, 8.380)	(6.913, 8.450, 9.283)
I29	(3.945, 5.680, 7.085)	(3.551, 5.275, 6.871)	(4.123, 5.755, 6.968)
I30	(4.450, 6.110, 7.560)	(6.203, 7.755, 8.588)	(7.178, 8.706, 8.994)
I31	(4.968, 6.615, 8.263)	(2.839, 4.568, 6.296)	(4.061, 5.738, 7.189)
I32	(3.465, 5.080, 6.185)	(1.654, 3.256, 4.795)	(1.956, 3.638, 5.319)
I33	(3.145, 4.900, 6.325)	(2.139, 3.841, 5.480)	(3.375, 5.100, 6.600)

Table 6. Development of the FMEA for issues found in the university.

RPN Sequence	AP Level	DSi	DOi	DDi	R	Item
1	H	7.640	7.008	7.520	402.600	I6
2	H	6.040	7.515	8.293	376.402	I30
3	M	6.415	6.985	8.215	368.104	I28
4	H	8.660	8.050	2.998	208.965	I4
5	M	6.615	4.568	5.663	171.087	I31
6	L	5.570	5.233	5.615	163.649	I29
7	M	4.790	4.750	6.858	156.025	I15
8	M	4.590	4.972	6.532	149.062	I22
9	L	5.945	3.837	6.255	142.661	I14
10	M	4.065	5.073	6.893	142.121	I21
11	L	4.680	4.895	6.170	141.346	I27
12	L	5.260	4.450	6.033	141.203	I23
13	L	5.420	4.313	5.858	136.912	I26
14	M	5.480	5.808	4.290	136.530	I10
15	L	5.360	5.028	4.823	129.954	I1
16	L	5.455	5.463	4.333	129.100	I17
17	M	6.545	4.021	4.622	121.649	I19
18	M	4.290	5.945	4.744	120.985	I13

Table 6. *Cont.*

RPN Sequence	AP Level	DSi	DOi	DDi	R	Item
19	L	6.445	4.321	3.960	110.276	I16
20	L	5.145	5.243	3.998	107.823	I3
21	L	5.265	4.809	4.055	102.665	I12
22	M	6.925	3.773	3.875	101.233	I8
23	L	4.790	3.820	5.025	91.946	I33
24	L	4.290	3.750	5.615	90.331	I25
25	L	4.635	5.118	3.773	89.482	I18
26	L	5.635	3.959	3.898	86.953	I11
27	L	3.280	3.721	6.315	77.079	I24
28	L	3.649	4.474	4.470	72.982	I5
29	L	3.975	3.000	5.985	71.371	I2
30	L	4.910	3.235	3.638	57.778	I32
31	L	3.705	3.278	4.655	56.526	I9
32	L	3.180	4.050	3.262	42.012	I7
33	L	3.445	3.410	3.132	36.794	I20

Upon conducting research on the campus accessibility system, it was identified that there are significant issues pertaining to accessibility, convenience, and hazards. Regarding accessibility, a specific proportion of buildings do not have entrances and exits that are accessible, elevators that are accessible, and have classroom doors that lack windows. This renders certain areas unattainable for individuals with physical disabilities without assistance. Regarding convenience, the allocation of accessible toilets is uneven, and the size of certain facilities is unreasonable. This has an adverse effect on daily usage and is not sufficiently convenient. Hidden dangers exist in terms of safety, such as inadequate facility size and the absence of canopies at building entrances and exits. Owing to the unique attributes of frigid regions, there are also handrails on ramps and door handles at entrances/exits that experience low temperatures in icy conditions. These elements pose a significant barrier to access and are highly susceptible to accidents. These issues also present a significant hazard and require immediate attention.

4.3. Comparison of Accessibility between the Old and New Campuses

Research indicates that the barrier-free facilities on the Nanhu and Hunnan Campuses differ significantly. The main facilities are listed, encompassing accessible entrances, ramps, ramp handrails, barrier-free elevators, barrier-free toilets, and the narrowest corridors. The percentage of compliant structures in the two campuses is calculated based on the criteria outlined in the General Barrier-Free Specification for Architectural and Municipal Engineering of China. The outcome of the comparative analysis is depicted in Table 7.

Table 7. Comparison of barrier-free facilities between the old and new campuses.

Type of Facility	Proportion of Qualified Buildings in Nanhu (Old) Campus	Proportion of Qualified Buildings in Hunnan (New) Campus
Accessible entrances	46.67%	96.00%
Ramp	26.67%	96.00%
Ramp handrails	26.67%	44.00%
Accessible elevators	20.00%	40.00%
Accessible toilets	33.33%	72.00%
The narrowest access corridor	100.00%	100.00%

Overall, the level of barrier-free facilities in the new campus has increased to a certain extent, but it is not perfect. The construction time difference between the two campuses is 91 years, which proves that during this period, the national and social awareness of accessible environment construction has grown relatively slowly and has not undergone essential changes.

In the construction of campus barrier-free facilities, more attention is usually paid to central buildings, where the more important and open management is located, or to more open public buildings, such as comprehensive buildings, libraries, etc. Relatively speaking, the barrier-free facilities in canteens, activity centers, teaching buildings, and other buildings commonly used by student groups are often ignored. For example, the installation of accessible elevators has achieved a compliance rate of 40% for the new campus and 20% for the old campus. The comprehensive buildings and libraries in both campuses are equipped, but all dormitories within 6 floors do not have elevators, although the dormitory user groups are more likely to have needs for accessible environments. From this point of view, schools may pay more attention to the work experience of management or teachers and relatively ignore the needs of student groups.

Judging from the differences between the old and new campuses. The number of buildings equipped with barrier-free toilets in the new campus reached 72%, and the pass rate is twice that of the old campus. In terms of barrier-free entrances and ramps, 96% of the buildings in the new campus meet the construction standards, while the figures in the old campus are 46.67% and 26.67%, respectively. Perhaps due to later additions, some ramps in the old campus are far away from the entrances and exits, so the pass rate is low. Managers are lax in inspecting and maintaining slopes, and falling snow is not cleared in time, which affects the safe travel of wheelchair users. The construction and management measures of relevant facilities in the new campus are more complete, meeting the daily needs of the user groups. Compared with the old campus, the new campus pays more attention to typical barrier-free facilities such as accessible toilets and elevators, but the details are still not in place. For example, the sudden appearance of thresholds, debris piled in accessible toilets, steps at the end of ramps, etc. These details make the barrier-free facilities that are focused on construction unable to be used effectively.

However, in the recent five years, several new buildings were constructed on both campuses. These buildings have received much attention in terms of accessibility. Taking the setting of barrier-free toilets as an example, the new building not only ensures that there are barrier-free toilets on every floor, but it also tries to avoid height differences in every ordinary pit. The restrooms set up in the earlier constructed buildings on both campuses have some elevation difference in the pit set up due to construction issues. This is not accommodating for individuals with disabilities or those with leg injuries or other lower limb mobility issues, indicating that the school did not sufficiently prioritize the overall design of the restrooms during the initial construction phase. It also proves that in recent years, various groups have gradually realized the importance of universal design, which is an advancement in the awareness of accessibility.

In summary, in order to improve the campus accessibility system, the Northeastern University should focus on supplementing and improving the accessibility facilities on the old campus and strengthening supervision and management, as well as conducting regular maintenance of the existing barrier-free facilities. Moreover, the two campuses should not only build sufficient and reasonable facilities, but also pay attention to the systematic construction of the accessible environment to ensure effective connection between the facilities. Also, they should further strengthen the focus on the student community and try to meet the different types of accessibility needs of users in order to encourage equal participation and inclusive development of marginalized groups.

4.4. Relevant Analysis of Existing Issues

In addition to the seven items listed in Table 6, namely I6, I30, I28, I4, I31, I15, and I22, which have higher ratings in both AP classification and RPN ranking, we conducted interviews with a team of experts to examine and analyze the accessibility of each facility mentioned in the question. This investigation was carried out in accordance with the Code of Practice.

The highest priority, I6, relates to the issue of low temperatures of ramp handrails. Based on the research findings, the handrails on the ramps at Northeastern University's campus are constructed entirely from iron. Additionally, the average winter temperature in this location is −14.4 °C, with occasional extreme temperatures dropping as low as −25.2 °C. Iron handrails are predominantly found on major campuses worldwide. Nevertheless, in frigid areas, exposed iron handrails can result in unfavorable encounters for individuals and potentially even frostbite. The Code does not address this issue, suggesting the absence of legislation in specific areas and the necessity for managers to proactively resolve the problem, such as changing the handrail material or wrapping the handrail. The issue of low temperatures affecting door handles at accessible entrances and exits, typically made of plastic, is exemplified by I15. Despite being made of plastic, these handles still present a risk of frostbite in cold weather. Nevertheless, some administrators have covered the door handles of buildings with cloth, considering the requirements of the users.

I28 emphasizes the disproportionate size of the handrails in the accessible toilet. According to the Code, accessible toilets must have two levels of handrails, with the upper handrail at a height of 0.90 m and the lower handrail at a height of 0.65 m. The mean height of the upper handrail in this school is 0.73 m, while the mean height of the lower handrail is 0.58 m. These measurements are comparatively below the dimensions mandated by the Code. Nevertheless, the team's communication indicated that implementing this change would not have a substantial effect on usage, would pose fewer risks, and would be more economical to retrofit. I31 highlights the issue of disproportionately large accessible restrooms. According to the Code, accessible toilets must have a clear width and depth that consider the turning radius of a wheelchair, and both dimensions should be larger than 1.5 m. Accessible toilets at the university had varying widths, ranging from 0.89 to 2.4 m, with an average width of 1.9 m. The depth of these toilets also varied, ranging from 0.54 to 8.1 m, with an average depth of 1.3 m. The facilities met the standard requirements. Several of the accessible restrooms are undersized as a result of delayed construction and inadequate space. To enhance the campus accessibility system, it is crucial to prioritize the placement of accessible toilets in future construction projects.

I30 emphasizes the inequitable allocation of accessible restroom facilities. Based on the research findings, the university possesses a total of 23 buildings that are equipped with toilets that are easily accessible. The compliance rate for these facilities stands at 57.50%. According to the Code, public buildings must have at least one public restroom on each floor that meets the accessibility requirements for both males and females. Alternatively, they can have at least one separate accessible toilet located near the male and female public restrooms. Nevertheless, the survey indicates that individuals with restricted access, such as those with disabilities, tend to utilize the accessible restrooms located on the building's ground floor. For instance, the majority of the university's dormitory buildings only provide accessible toilets on the first floor, which adequately meets their needs. Installing the system on each floor may impede the managers' ability to effectively maintain it. Given the campus's inclusive and human-centered design, the team deems it essential to incorporate accessible restrooms on every floor of the main buildings, including the library and the main academic building.

I4 addresses the problem of snow buildup on ramps. Research indicates that 90% of the school's ramps remain covered in snow one day after a snowfall. If the ice and snow on the ramp are not promptly removed, there is a significant risk of falling, which can result in severe consequences. While the local legislation does not explicitly address this issue, it is challenging to exclude it from a universal design specification. We suggest enhancing supervision at the managerial level or the establishment of a group of campus volunteers to promptly and efficiently clear snow.

I22 indicates the elevator's brief moment of closing. Based on the research findings, the mean duration for the elevator door to open in this school is 6.3 s, with a minimum duration of 3 s. All of them satisfy the criteria outlined in the Code: the duration for closing the door is not less than 3 s. This issue necessitates a comprehensive resolution during the design phase. Rapidly closing elevator doors can result in the formation of crowds and increase the chances of falling, posing a potential hazard. It is advisable to install cautionary signs on the elevator doors to alert individuals about the potential hazards.

5. Discussion

5.1. Related Discoveries

Based on our research results, we found that the reasons for the failure of campus barrier-free facilities can be attributed to four aspects: awareness, system, management, and use.

In terms of awareness, although the construction results of barrier-free facilities in the new campus have improved compared with the old campus, there is still a lot of room for improvement. Many failure modes of barrier-free facilities are common to the new and old campuses. Many problems have not been effectively solved due to the difference in time. Perhaps due to insufficient funds or the small number of individuals with mobility impairments, the campus does not install barrier-free facilities in every building equally, effectively, and adequately. Even these buildings are necessary for students and teachers to use in their daily lives. Administrative office buildings that represent the image of the school tend to have higher accessible design priorities.

In terms of the system, we have not found any legal documents on barrier-free design in cold areas. Therefore, accessible construction in cold areas can only be based on the legal norms stipulated by the state. These legal norms are often the most universal standards, and there may be some unpredictable aspects in cold areas. In addition, in the questionnaire survey, we found that experts and individuals with mobility impairments hope that barrier-free facilities can be made more complete and convenient. This requires local governments to introduce more stringent and standardized standards. It is also necessary for campuses to strictly abide by legal provisions and proactively improve the construction standards of barrier-free facilities based on actual needs.

In terms of management, campus managers have some subjective management methods, which have a greater impact on the services of the facilities. For example, some managers will lock the barrier-free toilets most of the time, or treat it as a utility room for sanitary utensils, prohibiting normal use. Managers reduce the public's use opportunities and reduce the maintenance of facilities, but they also reduce their service efficiency. For another example, because the winter on some campuses is extremely cold, some administrators wrap special cloth on the door handles at the entrance of the building, which can greatly improve the people's experiences.

In terms of use, the user groups of these facilities, which include young students and individuals with disabilities, may also exhibit subjective behaviors towards the facilities in question, thereby impacting their operational efficacy. For instance, we discovered that certain buildings suffer from the issue of stairwells being littered, with the original space being obstructed by closets and sanitary appliances, thereby impeding access. Another instance is that in regions with interconnecting passageways, it is imperative to maintain the fire doors in a closed position. Nevertheless, the students wedged the doors into a typically unobstructed position to facilitate entry. This disregards the risks posed by fire and other dangers, and goes against the original intentions of the designers and norm creators.

In addition, we have also found several other flaws. While the toilets and elevators in certain buildings on the Hunnan Campus are equipped to accommodate individuals with disabilities, there is a lack of accessible entrances or ramps on the exterior. Consequently, wheelchair users are unable to enter the buildings independently and benefit from these inclusive designs. It can be seen that the accessibility system of the campus involves different groups of people at the management level, the utilization level, and the design level. Further, a lot of rough or even wrong treatment methods leads to these facilities not being used properly.

5.2. Research Deficiencies and Directions for Progress

There are limitations in this research as it only focuses on individuals with mobility impairments, neglecting to include visually impaired individuals. The distribution of individuals with physical impairments in the school is uneven, and the sample size of individuals with disabilities collected in the research is small. Thus, the data obtained may contain some degree of error.

In the future, our research will include a comprehensive survey of all colleges and universities in Shenyang, China. The campuses will be classified into distinct categories according to their year of construction in order to obtain a more rational analysis of the accessibility system of cold campuses. The evaluation indicators and methods will be further refined, incorporating more objective and quantitative data and information. In addition, greater attention will be devoted to individuals with visual and auditory impairments, with research specifically targeting educational institutions catering to disabled individuals.

6. Conclusions

This research provides a thorough examination of the accessibility infrastructure of a campus with a cold climate. A fuzzy-FMEA analysis was performed to address the shortcomings of conventional FMEA and enhanced the precision and reliability of the evaluation. Out of the 33 issues we identified, the ones that had the highest RPN (Risk Priority Number) and AP (Action Priority) ratings were the icing of ramps, low temperature of handrails, uneven distribution of accessible toilets, unreasonable size of handrails and spaces, low temperature of accessible entrance/exit door handles, and short closing time of elevators. These issues will be prioritized in the future. After evaluating the legal standards, the panel of experts reached the following conclusions: (1) both the new and old campuses' accessible designs have common issues, and the new campus's accessible environment's construction outcomes have not substantially improved; (2) the accessibility environment of the campus ignores the needs of students as the main group to a certain extent; (3) in China's cold regions, there is a lack of research specifications for accessible environments, and universal design is difficult to meet needs; (4) attention should be paid to the maintenance of facilities in the campus barrier-free system, and managers should pay more attention to barrier-free facilities; (5) the campus accessibility system encompasses the design layer (architects, engineers), the management layer (administration, campus logistics), and the user layer (primarily consisting of students). The failure of on-campus accessible environment construction may be affected by many factors, and it is important to coordinate the needs of the stakeholders.

However, in addition to the above problems, there is also a positive side to the barrier-free construction of the Northeastern University. In the recent five years, new buildings were constructed on both campuses, both of which have relatively good accessible facilities, including barrier-free entrances, barrier-free toilets, and usually complete ramp systems. It can be concluded that in recent years, the school has increased the significance of the accessibility system and is actively improving the accessibility of the campus. It is anticipated that future building results will be more comprehensive.

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References

1. General Office of the State Council of the People's Republic of China (GOSC). Notice of the State Council on Issuing the "National Human Rights Action Plan of China (2016–2020)". 2016. Available online: https://www.gov.cn/zhengce/content/2016-09/06/content_5105757.htm (accessed on 15 February 2024).
2. General Office of the State Council of the People's Republic of China (GOSC). Notice of the State Council on Issuing the "Equality, Participation and Sharing: 70 Years of Protecting the Rights and Interests of Persons with Disabilities in New China". 2019. Available online: https://www.gov.cn/zhengce/2019-07/25/content_5414945.htm (accessed on 15 February 2024).
3. Xiang, Z.R.; Zhi, J.Y.; Dong, S.Y.; Li, R.; He, S.J. The Impacts of Ergonomics/Human Factors of Wheelchair/User Combinations on Effective Barrier-Free Environments Design: A Case Study of the Chinese Universal Rail Coach Layout. *Int. J. Ind. Ergon.* **2018**, *67*, 229–241. [CrossRef]
4. Danillo, C.; Larissa, S.; Carla, F.; Rubens, L. Accessibility at University Campus in Historical Center. *Congr. Int. Ergon. Assoc.* **2018**, *824*, 1613–1621. [CrossRef]
5. Heylighen, A.; Van der Linden, V.; Van Steenwinkel, I. Ten Questions Concerning Inclusive Design of the Built Environment. *Build. Environ.* **2017**, *114*, 507–517. [CrossRef]
6. Hassan, M.A. Overview of Public Transportation Services for the Transportation Handicapped Persons in the United States. Ph.D. Thesis, Texas A&M University, College Station, TX, USA, 1990. Available online: https://www.proquest.com/openview/54632525512fef8248d9d00bcd1a3182/1?pq-origsite=gscholar&cbl=18750&diss=y (accessed on 13 February 2024).
7. Jo, C.; Choi, J. BIM Information Standard Framework for Model Integration and Utilization Based on openBIM. *Appl. Sci.* **2021**, *11*, 9926. [CrossRef]
8. Prandi, C.; Barricelli, B.R.; Mirri, S.; Fogli, D. Accessible wayfinding and navigation: A systematic mapping study. *Univ. Access Inf. Soc.* **2023**, *22*, 185–212. [CrossRef]
9. Zallio, M.; Clarkson, P.J. The Inclusion, Diversity, Equity and Accessibility audit. A post-occupancy evaluation method to help design the buildings of tomorrow. *Build. Environ.* **2022**, *217*, 109058. [CrossRef]
10. Gillett-Swan, J.K.; Burton, L.O. Amplifying children's voices: Sustainable Development Goals and inclusive design for education and health architecture. *Int. J. Speech-Lang. Pathol.* **2023**, *25*, 87–91. [CrossRef]
11. Zahari, N.F.; Che-Ani, A.I.; Abdul Rashid, R.B.; Mohd Tahir, M.A.; Amat, S. Factors Contribute in Development of the Assessment Framework for Wheelchair Accessibility in National Heritage Buildings in Malaysia. *Int. J. Build. Pathol. Adapt.* **2020**, *38*, 311–328. [CrossRef]
12. Tam, V.W.Y.; Fung, I.W.H.; Tsang, Y.T.; Chan, L. Development of a Universal Design-Based Guide for Handrails: An Empirical Study for Hong Kong Elderly. *Sustainability* **2018**, *10*, 4233. [CrossRef]
13. Li, J.; Zhang, C.; Cai, X.; Peng, Y.; Liu, S.; Lai, W.; Chang, Y.; Liu, Y.; Yu, Y. The Relation between Barrier-Free Environment Perception and Campus Commuting Satisfaction. *Front. Public Health* **2023**, *11*, 1294360. [CrossRef]
14. Osman, M.M.; Radzi, F.H.M.; Bakri, N.I.M.; Ibrahim, M. Barrier-Free Campus: University Malaya, Kuala Lumpur. *Procedia-Soc. Behav. Sci.* **2015**, *168*, 134–144. [CrossRef]
15. Stetieh, H. An Evaluation of the School of Engineering Buildings at the University of Jordan with Regard to Accessibility. *Sustain. Cities Soc.* **2018**, *42*, 240–251. [CrossRef]
16. de Velasco Machado, L.; de Oliveira, U.R. Analysis of Failures in the Accessibility of University Buildings. *J. Build. Eng.* **2021**, *33*, 101654. [CrossRef]
17. Murphy, M.; Heaney, G.; Perera, S. A Methodology for Evaluating Construction Innovation Constraints through Project Stakeholder Competencies and FMEA. *Constr. Innov.* **2011**, *11*, 416–440. [CrossRef]
18. Liu, H.C.; You, J.X.; Li, P.; Su, Q. Failure Mode and Effect Analysis Under Uncertainty: An Integrated Multiple Criteria Decision Making Approach. *IEEE Trans. Reliab.* **2016**, *65*, 1380–1392. [CrossRef]
19. De Oliveira, U.R.; Marins, F.A.S.; Rocha, H.M.; Salomon, V.A.P. The ISO 31000 Standard in Supply Chain Risk Management. *J. Clean. Prod.* **2017**, *151*, 616–633. [CrossRef]
20. Zadeh, L.A. Fuzzy Sets. *Inf. Control* **1965**, *8*, 338–353. [CrossRef]
21. de Aguiar, J.; Scalice, R.K.; Bond, D. Using Fuzzy Logic to Reduce Risk Uncertainty in Failure Modes and Effects Analysis. *J. Braz. Soc. Mech. Sci. Eng.* **2018**, *40*, 516. [CrossRef]
22. Ivančan, J.; Lisjak, D. New FMEA Risks Ranking Approach Utilizing Four Fuzzy Logic Systems. *Machines* **2021**, *9*, 292. [CrossRef]
23. Wang, W. Evaluating New Product Development Performance by Fuzzy Linguistic Computing. *Expert Syst. Appl.* **2009**, *36*, 9759–9766. [CrossRef]

24. Chen, S.; Yu, H.; Sang, T. Waste Management of Inspection Institutions Based on Fuzzy FMEA Analysis Method. *Res. Explor. Lab.* **2019**, *38*, 298–302. Available online: https://jglobal.jst.go.jp/en/detail?JGLOBAL_ID=202002292045352109 (accessed on 27 January 2024).
25. Wei, K.; Geng, J.; Xu, S. FMEA Method Based on Fuzzy Theory and D-S Evidence Theory. *Syst. Eng. Electron.* **2019**, *41*, 2662–2668.
26. Zhang, Y.; Li, K.; Chang, J. Risk Assessment of CNC Machine Tool Failure Mode Based on Fuzzy FMEA. *Machinery* **2020**, *58*, 44.
27. Li, X.; Gao, Q.; Liu, J. An Improved FMEA Risk Assessment Method Considering the Fuzzy Common Cause Failures. *Modul. Mach. Tool Autom. Manuf. Tech.* **2017**, *10*, 69. [CrossRef]
28. AIAG & VDA. *America. Failure Mode and Effects Analysis FMEA Handbook*; Automotive Industry Action Group: Southfield, MI, USA, 2019.