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Intelligent Systems Integrating BIM and VR for Urban Subway Microenvironmental Health Risks Management

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Abstract: With the rapid development and construction of urban subways, various risks associated with human health and wellbeing within subway microenvironments have seriously increased. However, only a few intelligent systems have been validated as suitable for facilitating the management of subway environments. Field tests can be time-consuming and inefficient, and questionnaires often lack true intuitiveness for participants. Therefore, to enhance subway environment management, this study proposed intelligent systems that integrate building information modeling (BIM) and virtual reality (VR) for managing health risks in urban subway microenvironments. The systems were developed using Revit 2021, Navisworks 2020, Unity 2019, MYSQL 8.0, and Visual Studio 2019. Additionally, they were applied in scenarios for environmental assessment and passenger coping capability enhancement, differentiated into an expert visual-based health risk assessment system and a gamified simulation system for passenger risk prevention. The feasibility of the approach was validated with the case of Xinzhuang subway station of Line 3 in Nanjing, China. The findings revealed that the assessment system enabled experts to have a better and straight understanding of subway microenvironmental health risks and the gamification simulation system significantly enhanced the passengers' coping capacity. The integration of BIM and VR, with its design features such as visibility, optimization, and simulation, compensated for BIM's lack of providing an immersive experience for systems. The intelligent systems introduced in this study present novel models for environmental assessment and passenger training, catering to both subway operators and researchers. The innovative systems serve as a cornerstone in guaranteeing the health and safety of public transportation operations.

Keywords: urban subway; building information modeling; virtual reality; risk assessment; microenvironmental health risks; coping capacity

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Citation: Chen, Q.; Li, C.; Xu, X.; Mao, P.; Xiong, L. Intelligent Systems Integrating BIM and VR for Urban Subway Microenvironmental Health Risks Management. *Buildings* **2024**, *14*, 1912. https://doi.org/10.3390/buildings14071912

Academic Editor: Jiying Liu

Received: 22 February 2024
Revised: 28 May 2024
Accepted: 14 June 2024
Published: 22 June 2024

1. Introduction

Urban subways, renowned for their speed and capacity, are prevalent across 79 countries, including Japan, the United States, Korea, China, Brazil, Chile, and Colombia [1,2]. Globally, subway networks spanned approximately 36,854.20 km in 2021, facilitating nearly 39.67 billion passenger journeys [3]. Despite being a vital mode of transport, exposure to microenvironments within subways—such as platforms, halls, and carriages—poses significant health risks. Airborne particles in these areas often contain heightened levels of iron, manganese, chromium, nickel, and copper, posing severe health hazards [4,5]. Furthermore, concentrations of PM, CO_2, VOCs, bacteria, and fungi in underground stations exceed permissible limits set by WHO, ASHRAE, and US EPA by 1.1–13.2 times [6]. Excessive exposure to respirable particulate matter can exacerbate chronic health conditions like lung dysfunction and chronic obstructive pulmonary disease [7]. The predominantly underground nature of subways, with limited natural ventilation, can also facilitate virus transmission [8], leading to concerns about passenger safety and health [9].

The growing concern over health risks in urban subway microenvironments has spurred interest [10]. Addressing these concerns requires intelligent systems. Current research often relies on field tests and questionnaires to study subway microenvironmental health risks [11–13]. For instance, questionnaires involving 399 subway construction professionals aimed to understand factors impacting the safety of Chinese subway projects [11]. Additionally, tools like air velocity meters and portable CO_2 analyzers were used to assess environmental quality in Nanjing's subway system [13]. However, field tests are time-consuming and inefficient [14,15], often taking months or years to complete [16]. They also lack comprehensive scenarios [17,18], rarely covering extreme risk levels simultaneously. Ethical concerns further limit extreme scenario testing due to potential health risks to participants [19,20]. Questionnaires, while overcoming some field test limitations, have their drawbacks. Participants can only visualize scenarios through descriptions on paper, lacking the immersive experience of subway microenvironments [21]. To address these challenges, this study proposes intelligent systems capable of constructing comprehensive subway microenvironmental scenarios, efficiently collecting data, and providing an immersive experience to enhance passenger coping abilities.

This study integrated building information modeling (BIM) with virtual reality (VR) for the management of health risks in the urban subway microenvironment. In a broader context, BIM involves collaboration among individuals, information systems, databases, and software. It can encompass hardware, tangible and intangible resources, as well as knowledge. BIM in a stricter sense refers to the semantic database associated with the construction object, which accompanies it throughout its life cycle [22]. The rapid development of BIM and VR lays the foundation for establishing the approach. BIM, which is widely applied in the construction field, possesses characteristics of visualization and simulation. It also demonstrates a high capability to build a 3D subway environment with various scenarios. It could play a promising role in the operation of subways, especially in the management of microenvironments such as platforms, station halls, and carriages [23,24]. Moreover, VR allows for human-computer interaction through computer-generated simulations, creating a virtual environment. With the application of BIM and VR, participants can immerse themselves in subway platforms, halls, and carriages with different levels of humidity, light brightness, crowd density, and other site conditions in virtual environment.

This study aimed to overcome the shortcomings of lengthy and incomplete field tests and the lack of intuitiveness in questionnaires by creating a BIM and VR-combined system to facilitate subway environment management. Based on different application functions, systems included the assessment of health risks and the improvement of behavioral capacity by building a visualized 3D scene with BIM and providing an immersive experience with VR. Firstly, research on subway microenvironmental health risks using standard approaches and research applying BIM or VR are introduced respectively. Then, this study constructed a framework based on the proposed BIM-VR approach to develop an expert visual-based health risk assessment system and a passenger risk prevention gamification simulation system. Finally, the feasibility of systems was validated through a case study of Nanjing Subway Line 3 (Xinzhuang Station). This study introduced intelligent systems for assessing health risks intuitively and easily and improving passenger coping capacity in the subway microenvironment, which plays a pioneering and fundamental role for the healthy and safe operation of the public transportation. Actually, the intelligent system developed in this paper has already been applied as a data collection system in the study by Chen et al. (2024) to propose a decision support system for iterative intervention management of subway microenvironmental health risks [10].

2. Background

2.1. Research on Subway Microenvironmental Health Risk Using Standard Approaches

The concept of the microenvironment appears in the biological field initially, which refers to the intercellular matrix and the body fluid components within it [25]; it was subsequently expanded to numerous other fields. Concerning subways, the microenvironment is defined as an environment including the thermal environment, acoustic environment, light environment, or air quality, which is directly related to human activities [13]. Subway platforms, halls, and carriages are special microenvironments [26,27]. Since urban subways are relatively confined and full of passengers, they pose a significant threat to the health and comfort of passengers [10,28]. Continuous exposure to urban subways can lead to rapid changes in heart rate, pulmonary dysfunction, and cardiovascular diseases [29,30] but few intelligent systems have been proposed on how to assess the level of environmental risk intuitively and easily.

Currently, studies on subway microenvironmental health risks commonly employ methods such as field tests or questionnaires. However, both methods have significant limitations. Fewer intelligent systems have been proposed to address the shortcomings of the two methods and to better manage subway environments. Firstly, due to its advantages of reliable data and high accuracy, field tests are commonly employed in subway environmental management. Instruments such as portable carbon dioxide samplers and indoor air quality meters are commonly used in field tests. For example, in Barmparesos et al.'s (2016) study, CO_2 levels in the Athens subway system were measured using portable carbon dioxide samplers [31]. Similarly, the temperature and humidity in Shanghai metro stations were measured using indoor air quality meters [32]. However, field tests tend to be time-consuming and inefficient, and often require several months or even years to complete. Hsu et al. (2020) expended nine months exploring the air pollutants of the Taiwan subway [15]. Passi et al. (2021) even devoted nearly three years [14]. The field test can certainly provide accurate physicochemical data on the subway [33], but the approach is not comprehensive enough to assess the microenvironmental risks of the subway. For example, Martins et al. (2015) measured $PM_{2.5}$ exposure concentrations in subway carriages, with a minimum of 20.2 μgm^{-3} and a maximum of 91.3 μgm^{-3} but no intermediate concentrations (between 70 μgm^{-3} and 80 μgm^{-3}) of $PM_{2.5}$ exposure were obtained in the test [17]. And the average $PM_{2.5}$ concentration in the Hong Kong and Guangzhou subway was 10.2 μgm^{-3}, and 55 μgm^{-3}, respectively [18]. These values are significantly lower than that of ambient air quality standards (GB3095-2012) [34]. Therefore, the test data for Hong Kong and Guangzhou subway lack the scenarios with severe air quality microenvironments. The field test was conducted on the condition that scenarios were not comprehensive. Scenarios with different risk levels, especially extreme ones, rarely appear concurrently. Moreover, it is difficult to create scenarios of extreme conditions in real life too. Even if extreme scenarios could be created, it would challenge the health of subjects, which is a serious violation of the ethical principle (never endangering human health) [19,20]. Therefore, field tests inevitably have limitations of being incomplete and time-consuming.

Questionnaires can potentially overcome the above-mentioned limitations of field tests. The questionnaire is also a well-established approach to study subway microenvironmental health risk. Yang et al. (2022) applied questionnaires to analyze the thermal comfort of the subway in Harbin (China) on 19 and 21 December 2019 [12]. Han et al. (2015) designed questionnaires using thermal, air, light, acoustic, and overall comfort as the comfort measurement dimensions [35]. His team spent nearly 16 days in 2014 conducting a questionnaire survey of on-site passengers. Furthermore, Mao et al. (2022) also used questionnaires to investigate the sensitivity of subway passengers to microenvironmental health risks [36]. However, one limitation of this approach was that an immersive experience of the subway environment could not be achieved since subjects could only visualize various scenarios through descriptions from the paper [21], which was not intuitive, not to mention not experiencing the illumination and crowd density of subway microenvironments immersively.

2.2. Research Applying BIM or VR

BIM stands for building information modeling, which refers to the semantic database linked to the construction object, providing continuous support throughout its life cycle [22].

Simulating a 3D state will help optimize the management of buildings [37,38]. Therefore, BIM is widely used in the management of shopping malls, houses, schools, transportation infrastructure, etc. [39,40]. BIM, as a maturing technology, has the potential to build a figurative 3D urban subway based on two-dimensional information. It has been applied in the performance management of subway station, safety design for emergency evacuation of subway stations [41], and thermal comfort monitoring of subways [24]. However, the BIM platform fails to provide an immersive experience for systems. Therefore, VR is introduced. As technology advances, VR, AR, and MR are products of the integration of virtual and real worlds, with an increasing number of scholars integrating these technologies with BIM to achieve more powerful functionalities. For example, a BIM-AR system was proposed by implementing marker-based AR, enabling the viewing, interaction, and collaboration with 3D and 2D BIM data via AR among geographically dispersed teams [42]. El Ammari et al. (2019) achieved remote interactive collaboration in facilities management by integrating MR with BIM. In this study, VR technology was selected for integration with BIM [43]. VR can be defined as a three-dimensional computer-generated simulated environment, which attempts to replicate real world or imaginary environments and interactions, thereby supporting work, education, recreation, and health [44]. VR generates a virtual environment via computers and creates an immersive experience with the supplement of various devices such as HMDs, glasses, and multiple displays [45]. Introducing VR can lead to a better interactive immersive experience [46,47]. It provides experts with visual panoramic views of subways and engages passengers in immersive risk-coping behavior simulation.

The idea of combining BIM and VR has been widely applied in architecture, engineering, and construction [48]. Complemented with BIM, VR enables systems to provide an immersive experience for their users. However, VR has not been fully advanced in supporting construction information interoperability and with collaboration, which can be facilitated with BIM [49]. Therefore, on one hand, intelligent systems developed based on VR can provide users with immersive subway scene experiences. On the other hand, intelligent systems can also design different scenarios for simulation according to needs and quickly collect data through computer software, effectively addressing the incompleteness and time-consuming issues associated with field tests. The management efficiency of BIM-VR has been amply proved by cases such as building seismic loss prediction [50], on-site assembly services in prefabricated construction [26], and construction fire safety [51]. However, due to the complexity of large infrastructures such as the subway, the integration of BIM and VR is still at the infancy stage. Standard approaches (e.g., field tests and questionnaires) are still extremely popular for studying the management of subway microenvironmental health risks.

Therefore, to bridge the gaps from these existing standard research approaches, this study proposed intelligent systems for the management of the subway microenvironment. Based on different application functions, systems included the assessment of health risks and the improvement of behavioral capacity by building a visualized 3D scene with BIM and providing an immersive experience with VR. The goal of the research was to develop systems that combine BIM and VR to display the microenvironment of subways through virtual reality, facilitating the management of subway environments.

3. Methodology

3.1. Proposed Approach

Based on the proposed approach shown in Figure 1, researchers in this study developed systems to assess the risk levels of the subway microenvironment and coping capability, which allows for the interactive transmission information of dual users (experts and passengers).

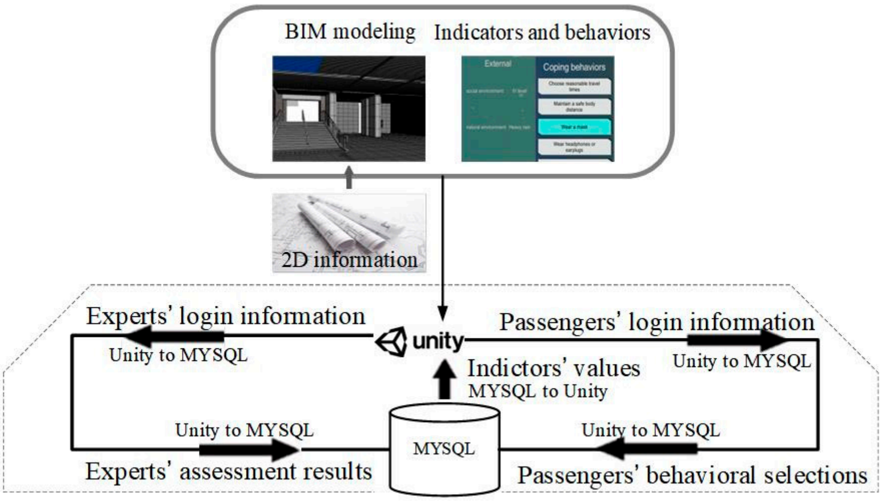

Figure 1. Proposed BIM-VR approach.

The specific BIM-VR approach should perform the following functions.

(1) Building a 3D visualization model based on 2D information via BIM.

BIM is an ideological concept that simulates the design, construction, and operational management processes of a project using 3D digital models [52]. Revit, as a specific BIM implementation software, was utilized to create and simulate a 3D digital model of the subway. This software enables the integration of information from basic components such as columns, beams, slabs, walls, and detailed components like holes, pipes, and preburied items [53]. It accurately constructs models based on 2D information and presents them in a three-dimensional format, providing a visual model that facilitates roaming simulation [54].

(2) Integrating three-dimensional BIM files, indicators, and coping behaviors to achieve a roaming experience.

Unity demonstrates an excellent compatibility with Revit, which supports FBX format files exported from Revit. BIM docks with Unity without obvious barriers, which can substantially ensure the integrity of the physical model of the urban subway. Moreover, as a powerful 3D game development engine, Unity is lightweight and functionally stable. It can operate safely and stably under Mac or Windows systems. Developers can apply Visual Studio as the C# script editor whose codes could program indicators and coping behaviors into the expert visual-based health risk assessment system and the passenger risk prevention gamification simulation system to construct the roaming VR scenario.

(3) Combining VR with MYSQL to facilitate the transmission of information from dual-users.

On one hand, Unity should read the indictors' values from MYSQL for systems development. On the other hand, the log-in information and the results of experts' risk assessment or the passengers' selections of coping behaviors need to be saved into MYSQL. Programming languages such as C# can implement the lap between Unity and MYSQL, which enables the interaction and transmission of dual-user.

Based on the proposed BIM-VR approach, we utilized Revit to construct a three-dimensional model of the subway, while interaction design was achieved via VR software such as Unity and external devices like head-mounted devices. In terms of data flow, this study combined Unity and MYSQL software to import expert and passenger information and save results. Ultimately, we developed an expert visual-based health risk assessment system and a passenger risk prevention gamification simulation system. During application, both experts and passengers wore head-mounted devices to enter the three-dimensional model of the subway station, experiencing textures on the walls, brightness of lights, and other elements. Through immersive roam in the subway station, they provided their respective risk assessments or coping behaviors.

3.2. Framework Development

This study investigated risk assessment and prevention gamification simulation systems of the urban subway microenvironment based on the BIM-VR framework. The framework consisted of the following parts: (1) setting indicators and coping behaviors; (2) building information modeling; (3) accepting front-end work for system development; (4) developing an expert visual-based health risk assessment system; and (5) developing a passenger risk prevention gamification simulation system. The system overcame the limitations of unintuitive questionnaires and time-consuming field tests by introducing the BIM-VR approach, assessing the risk level of the subway microenvironment, and enhancing passenger risk-avoidance coping capability. The BIM-VR framework is shown in Figure 2, and the software used is listed in Table 1.

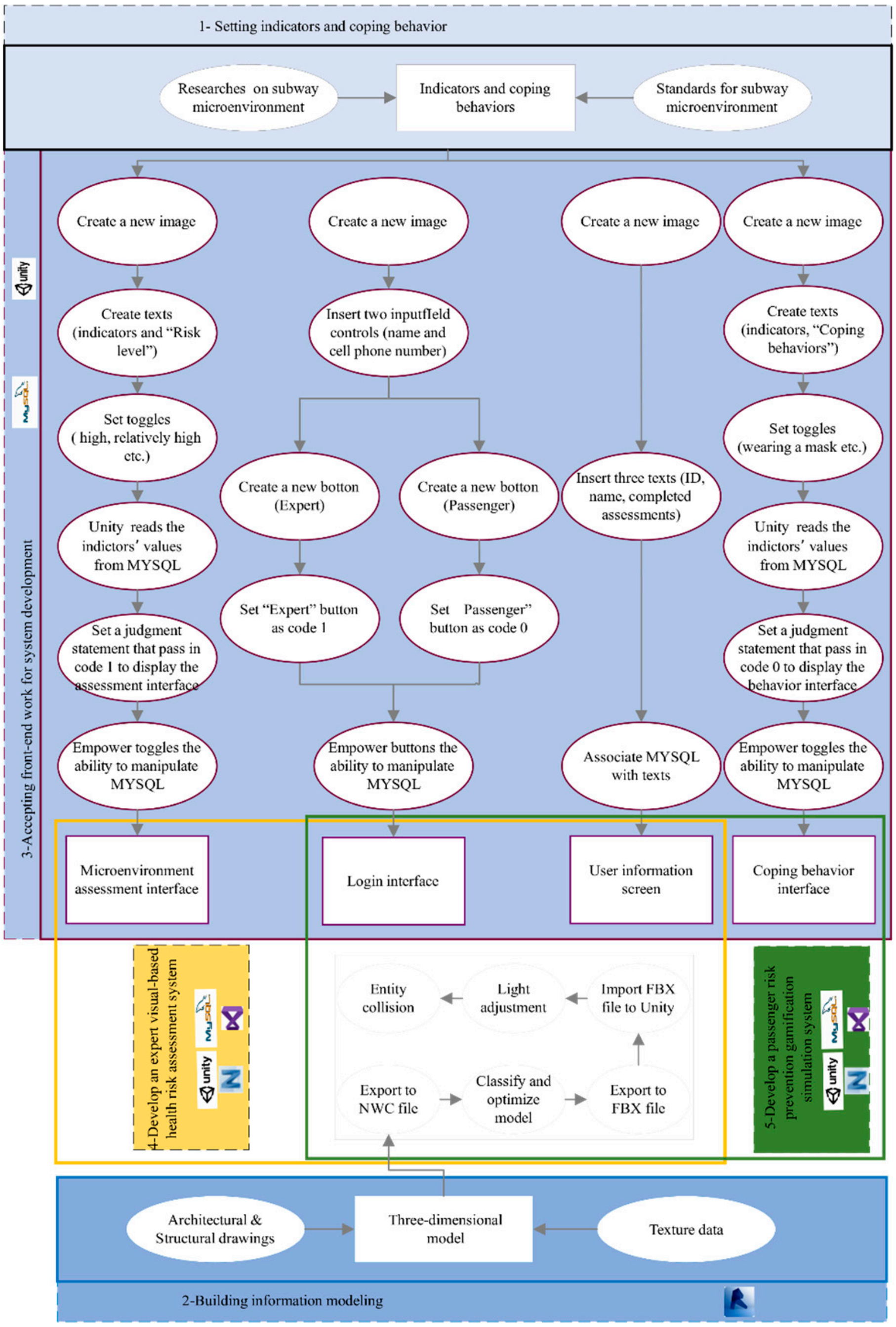

Figure 2. BIM-VR framework.

Table 1. Software used in the paper.

Software	Software		Function
BIM	Revit 2021	R	build a 3D model of the urban subway
	Navisworks 2020	N	classify and optimize the model
VR	Unity 2019	unity	provide an immersive experience for systems
	MYSQL 8.0	MySQL	import and export of simulation data
	Visual Studio 2019		function as the C# script editor

The different colors in Figure 2 respectively represent the five different steps: setting indicators and coping behaviors, building information modeling, accepting front-end work for system development, developing an expert visual-based health risk assessment system, and developing a passenger risk prevention gamification simulation system. As shown in Table 1, this study involved five software applications: Revit, Navisworks, Unity, MYSQL, and Visual Studio. Firstly, Revit is a BIM software that supports parametric modeling. Users can define the properties and behaviors of building elements by setting parameters and constraints, enabling intelligent modeling. Secondly, Navisworks is a project collaboration and coordination software used in the architecture, engineering, and construction industries. Its advantage lies in its ability to integrate model data from different design software, facilitating project collaboration and clash detection. Thirdly, Unity is used for developing VR, AR, and other interactive applications. It features powerful graphics rendering capabilities and user-friendly development tools. Additionally, MYSQL is an open-source relational database management system known for its stability, reliability, high performance, ease of use, and deployment. Lastly, Visual Studio is an integrated development environment used for developing various types of software applications. Its strengths include powerful development tools, extensive plugin support, intelligent code editor, and convenient debugging capabilities. For the above reasons, we chose these five software applications.

3.2.1. Setting Indicators and Coping Behaviors

It is crucial to establish subway microenvironmental health risk indicators. These indicators can be derived from existing research on subway microenvironments [55–57] or based on standards such as the Ambient Air Quality Standards (GB3095-2012) and the Code for the Design of Subway (GB50157-2013) [34,58]. Additionally, for the simulation of risk avoidance games for passengers, it is recommended to categorize and list common coping behaviors based on previous studies [59,60]. The specific indicators and coping behaviors could be changed according to the actual application. Furthermore, assigning values to indicators should align with real-world scenarios and research requirements.

3.2.2. Building Information Modeling

This study employed BIM to depict the 3D representation of the subway microenvironment as the foundational step for developing subsequent systems. The initial phase of BIM modeling involved data collection, which comprised two key types of data. Firstly, architectural and structural drawings of the subway were essential, encompassing plan drawings, elevation drawings, section drawings, and detailed drawings of large samples. Secondly, texture data for the 3D model, such as material properties, coloring, gloss, and saturation of components, was crucial. In the subsequent step, Revit was utilized to process this data. Specifically, Revit was employed to construct internal elements like columns, beams, walls, and rebars of the subway, with adjustments made to their dimensions and materials through input parameters. This process resulted in the creation of a comprehensive 3D model of the urban subway. The details of the whole BIM model are presented in Figure 3.

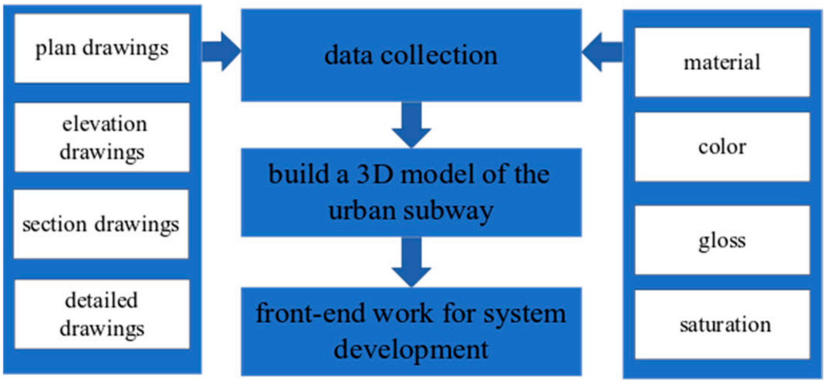

Figure 3. Details of building information modelling.

3.2.3. Accepting Front-End Work for System Development

The login interface and user information screen were created. Once users inputted their information and logged in, this data was connected to MySQL for storage. After logging in, the user information screen was displayed in the top left corner of the page, including the user's ID, name, and completed assessments. The new image (user information screen) and three new texts (ID, name, completed assessments) were created. The texts associated with MYSQL to display the latest ID, name, and completed assessments. The user information screen is shown in the upper left corner of Figures 4 and 5.


ID:0
Tester01 Hello!

Personnel data done

Environmental data done

Management data done

External data done

Gather data close to the photosphere
(Platform level left) Collected 4/5

Figure 4. Details of building information modelling (floor one).

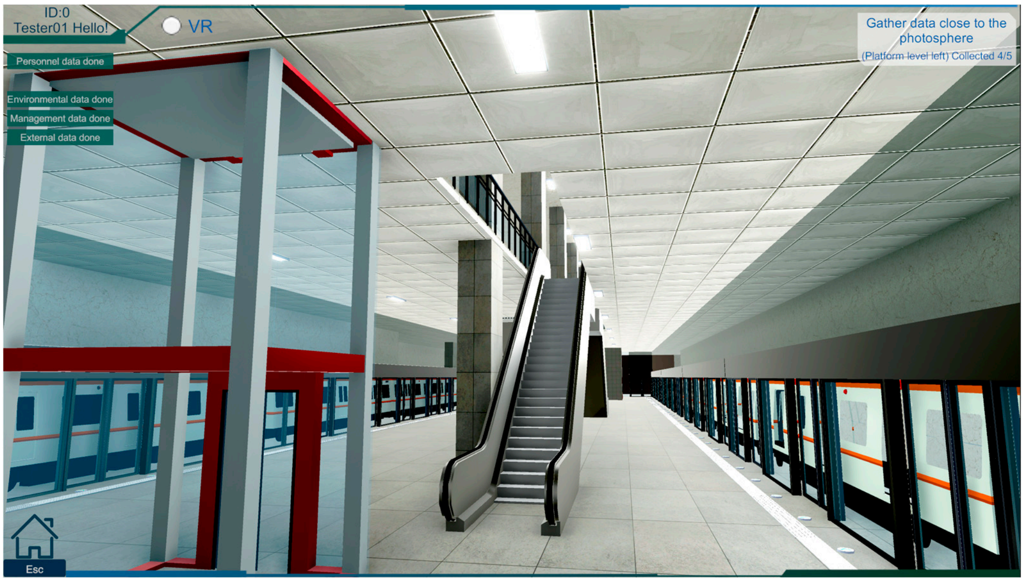

Figure 5. Details of building information modelling (floor two).

Two microenvironmental management interfaces of experts' assessment and passengers' coping behaviors were designed to achieve different functions. An image as a background in the panel and some new texts (indicators, "Risk level" or "Coping behaviors") were created. Control toggles that were already filled with the risk level ("high, relatively high, medium, relatively low, and low") or specific coping behaviors such as "wear a mask" were set on the right side of the interfaces (Figures 6 and 7). Then, indicators' values in MYSQL were read by Unity. The judgment statements that passed in code 1 to display the assessment interface and passed in code 0 to display the coping behavior interface were set in the interface code. Thus, selecting the "Expert" button led to the expert vision-based health risk assessment system, whereas the "Passenger" button led to the passenger risk prevention gamification simulation system. Systems recorded assessment results and behavior selections in MYSQL by empowering toggles to manipulate MYSQL.


S1 Internal

illumination	250	<200>	PM2.5	55	<50>
temperature	28	<18–23>	CO2	2000	<1000>
humidity	90%	<30%–60%>	CO	8	<24>
wind	0.5	<0.5>	TVOC	0.4	<0.6>
noise	100	<70>	bacterium	4000	<4000>
PM10	350	<250>	flow density	3	<1>

Personnel

educational level	65%
technology level	85%
emergency skills	75%

External

social environment	Level IV
natural environment	Heavy rain

Equipment

infrastructure location pass rate	85%
emergency location pass rate	85%
infrastructure integrity	High
emergency integrity	Low
maintenance pass rate	85%
emergency effectiveness	Relatively low

Management

safety knowledge pass rate	65%
emergency drill effect	Relatively low
supervision system integrity	Medium
emergency plan integrity	Medium
supervision strength	Relatively high
risk investigation strength	Low
organizational coordination	Relatively low

Figure 6. The experts' assessment interface.

S1

Internal

illumination	250	<200>	PM2.5	55	<50>
temperature	28	<18–23>	CO2	2000	<1000>
humidity	90%	<30%–60%>	CO	8	<24>
wind	0.5	<0.5>	TVOC	0.4	<0.6>
noise	100	<70>	bacterium	4000	<4000>
PM10	350	<250>	flow density	3	<1>

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Management

safety knowledge pass rate	65%
emergency drill effect	Relatively low
supervision system integrity	Medium
emergency plan integrity	Medium
supervision strength	Relatively high
risk investigation strength	Low
organizational coordination	Relatively low

Coping behaviors

- Choose reasonable travel time
- Maintain a safe body distance
- Wear a mask
- Wear headphones or earplugs
- Avoid touching escalator,seat,handrail
- Stay calm and follow the instructions of the staff
- Evacuate according to safety evacuation signs
- Sound the emergency alarm
- Give suggestions to operating companies

Figure 7. The passengers' coping behaviors interface.

3.2.4. Developing an Expert Visual-Based Health Risk Assessment System

Firstly, the three-dimensional model was exported to a NWC file. With some of the nonvisible structural components hidden by Navisworks, the model was classified, optimized, and exported as an FBX file. The optimized FBX file was imported into Unity for light adjustment and entity collision to truly visualize the subway microenvironment scene. The illumination was adjusted by the light source setting function of the Unity software for realistic visual perception. To enhance the realism of roaming in the subway scene, this study controlled the "S", "W", "A", and "D" to shift the collider forwards and backwards, or laterally (colliding in the scene), and finally achieving the unity-based 3D subway station (Figures 8 and 9). Experts needed to roam the subway and continuously collect subway microenvironmental indicators. Eventually, all indicators were displayed in the microenvironment assessment interface. Experts were placed in the model of the 3D urban subway scene and delivered risk level assessments (high, relatively high, medium, relatively low, and low) based on the indicators displayed on the interface.

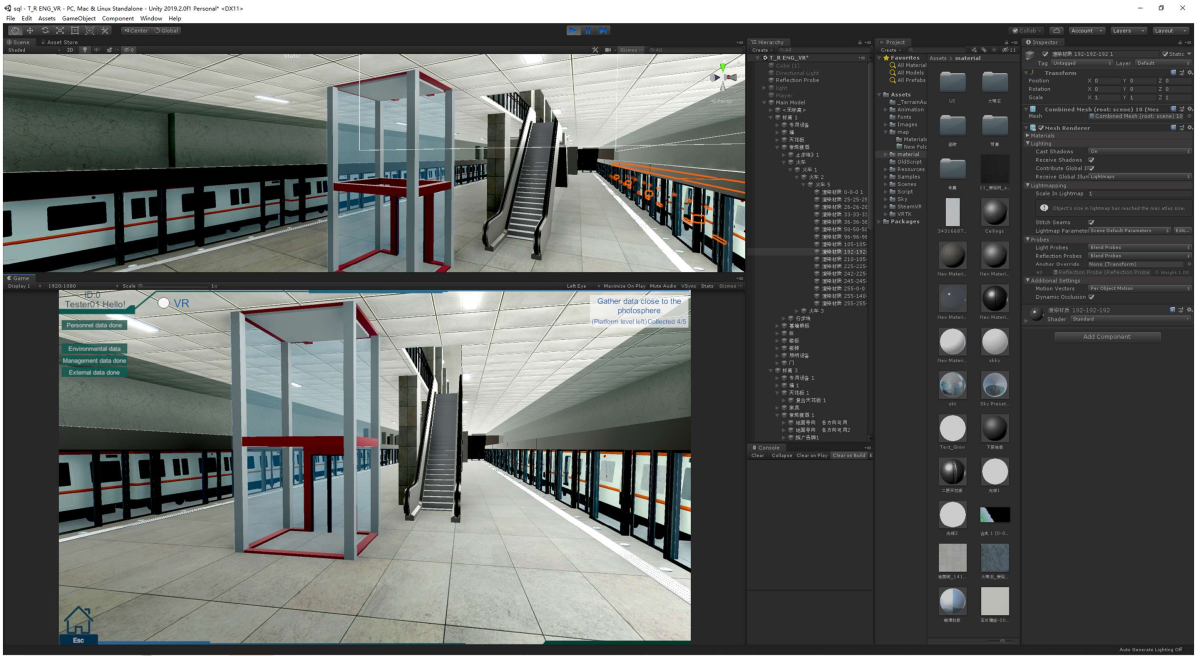


Figure 8. Unity-based subway station 3D rendering (floor two).

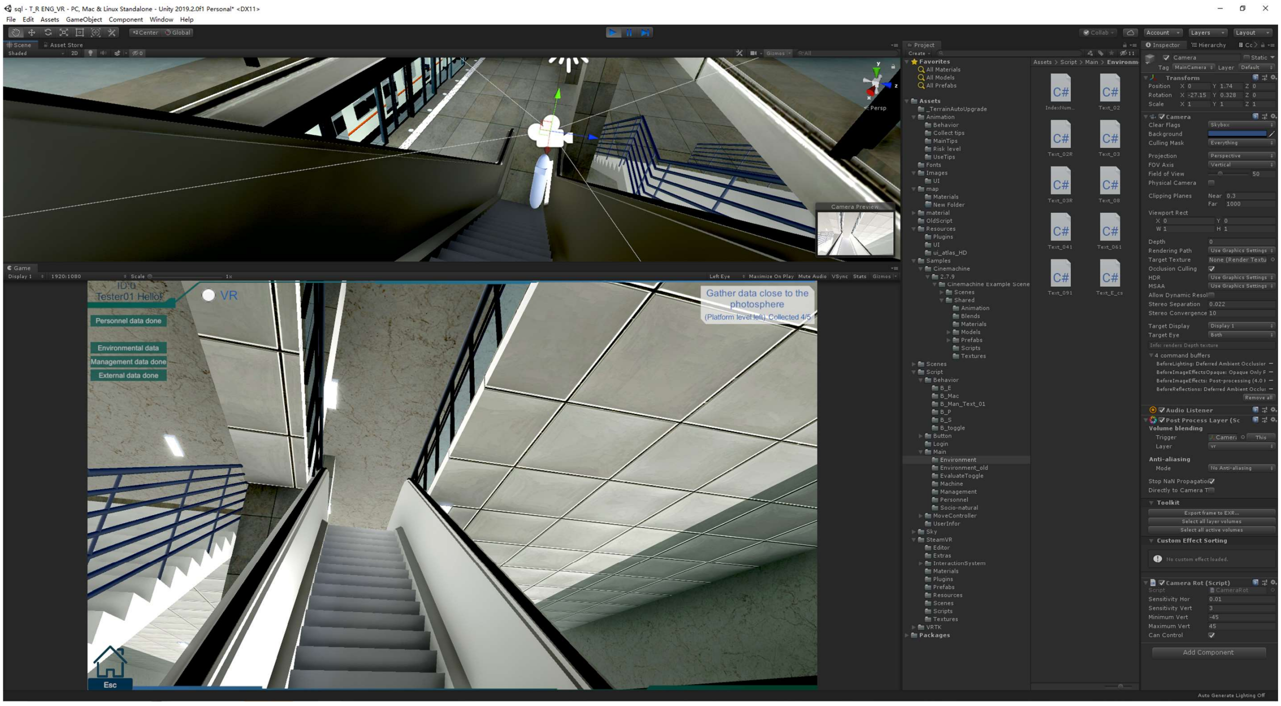


Figure 9. Unity-based subway station 3D rendering (elevator).

3.2.5. Developing a Passenger Risk Prevention Gamification Simulation System

Based on the urban subway model constructed via Revit and Unity, the same approach as an expert visual-based health risk assessment system was adopted to develop a passenger risk prevention gamification simulation system. Furthermore, passengers could immersively roam the interior of the 3D subway. The indicators and coping behaviors of passengers were displayed within the coping behavior interface. Passengers could choose their risk coping behaviors based on the information displayed in the interface.

4. Case Study

4.1. Setting of the Risk Indicators and Coping Behaviors

For the case study validating the proposed approach, we utilized BIM-VR systems based on Xinzhuang subway station of Line 3 in Nanjing. To comprehensively identify effective risk indicators, a search was conducted on "Web of Science" using the search string TS = [("subway" OR "metro" OR "underground") AND ("microenvironment" OR "environment") AND ("health risk" OR "risk")]. The results are presented in Table 2. It is essential to note that while these risk indicators are provided, their determination was not the primary focus of this study and could be adjusted based on specific practical considerations. The indicators are numbered in Table 2, such as A1 and A2.

Using a similar approach, we derived coping behaviors from the literature, identifying nine types, which are listed in Table 3. Further research may adjust these coping behaviors according to specific practical circumstances.

Table 2. Subway microenvironmental health risk indicators.

First-Level Indicators	Second-Level Indicators	References
Internal environment	Illumination (A1)	[13,61,62]
	temperature (A2)	[55]
	humidity (A3)	[56,57]
	wind (A4)	[18,63]
	noise (A5)	[64,65]
	PM_{10} (A6)	[66]
	$PM_{2.5}$ (A7)	[66,67]
	CO_2 (A8)	[68]
	CO (A9)	[27]
	TVOC (A10)	[68,69]
	bacterium (A11)	[56]
	flow density (A12)	[18]
External environment	natural environment (A13)	[70,71]
	social environment (A14)	[61,63]
Personnel	educational level (B1)	[72,73]
	technology level (B2)	[74–76]
	emergency skills (B3)	[72,77]
Equipment	infrastructure location pass rate (C1)	[77]
	emergency location pass rate (C2)	[77]
	infrastructure integrity (C3)	[78]
	emergency integrity (C4)	[74,79]
	maintenance pass rate (C5)	[75,78]
	emergency effectiveness (C6)	[78,80]
Management	safety knowledge pass rate (D1)	[81]
	emergency drill effect (D2)	[82,83]
	supervision system integrity (D3)	[76,84]
	emergency plan integrity (D4)	[82,83]
	supervision strength (D5)	[85,86]
	risk investigation strength (D6)	[86,87]
	organizational coordination (D7)	[82,88]

Table 3. Subway microenvironmental health risk coping behaviors.

Coping Behaviors	References	Coping Behaviors	References
Choose reasonable travel time	[36]	Wear headphones or earplugs	[36]
Wear a mask	[36]	Give suggestions to operating companies	[36]
Maintain a safe body distance	[59,60]	Avoid touching escalator, seat, handrail, and other	[89,90]
Stay calm and follow the instructions of the staff	[91]	Evacuate according to safety evacuation signs	[91]
Sound the emergency alarm	[92]		

4.2. Virtual Simulation

A total of 20 experts and 20 passengers were recruited in the case study, as a simulation typically involves dozens of individuals [42,93]. The information about the experts is shown in Table 4. Additionally, we randomly recruited 20 students who frequently use the subway to participate in the experiment as passengers. Since the purpose of this experiment was to verify that this system can be used for training and improving passengers' coping skills, the selection of subjects met the experimental needs.

Table 4. Expert structure.

Employer	Years of Employment	Educational Qualification	Count
round1			
subway department	5–10	master	3
subway department	5–10	bachelor	1
subway department	Over 10	master	2
subway department	Over 10	bachelor	3
university	Over 10	doctor	5
center for disease control	Over 10	doctor	6
round2			
subway department	5–10	master	2
subway department	5–10	bachelor	1
subway department	Over 10	master	2
university	Over 10	doctor	2
center for disease control	Over 10	doctor	3

Participants were given brief information about the study's purpose before deciding whether to participate. This study was conducted with the explicit consent of all participants, who were informed that the data would be used for research purposes. Each expert conducted 50 experiments, and 10 out of the initial 20 experts were selectively invited for a second round of experiments. The second round also included a passenger risk prevention gamification simulation, which provided standard answers for passenger coping behaviors. Additionally, each passenger then completed 10 experiments. To evaluate the effectiveness of passenger training based on Ebbinghaus' forgetting curve and the decline in memory retention over time, each passenger repeated the same 10 experiments two days later [94]. In total, the two rounds of experiments yielded 1500 expert samples and 400 passenger samples, with a 100% response rate.

On one hand, the experts logged in by entering their names, numbers, and clicking the "Expert" button. Upon accessing the visual risk assessment interface, experts roamed from the entrance to the interior of the subway station, a virtual environment built using Revit and Unity. During this immersive experience, they continuously collected subway microenvironmental indicators. All collected indicators were displayed on the microenvironment assessment interface, where experts provided a health risk assessment of the subway microenvironment. Since MYSQL was integrated with Unity, the results were recorded in MYSQL. Repeating the above steps (Figure 10), each expert evaluated 50 sets of scenarios, the data of which were randomly assigned.

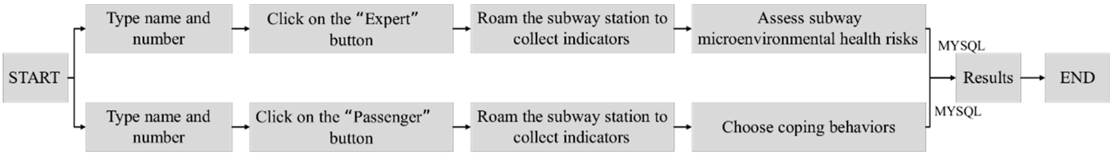


Figure 10. Work steps of the virtual simulation.

On the other hand, passengers logged in by entering their names, numbers, and clicking the "Passenger" button to start the gamification simulation. They navigated different locations within the Xinzhuang station system to collect indicators (Figure 11). Based on the information displayed on the subway microenvironment coping behavior interface, passengers selected coping behaviors from the options provided. Each passenger repeated these steps for 10 sets of scenarios. As MYSQL was integrated with Unity, all results were recorded in MYSQL. The entire immersive simulation process is illustrated in Figure 10.

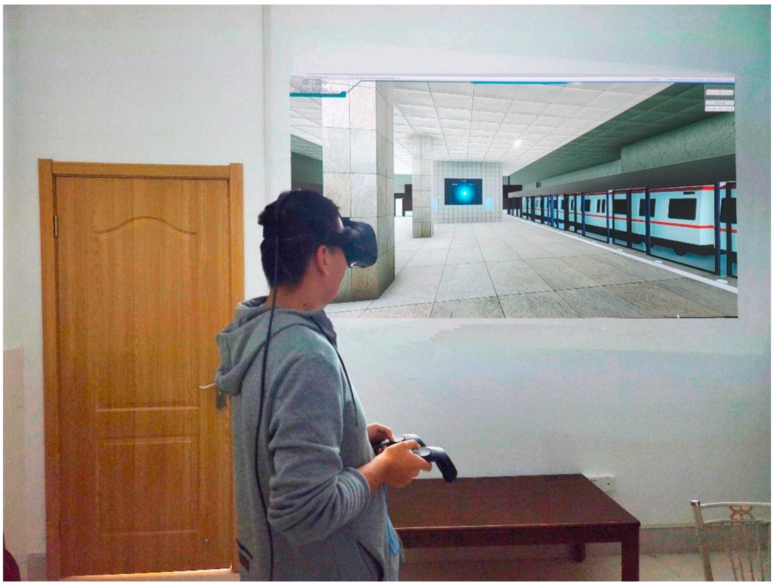


Figure 11. Immersive VR simulation.

5. Results

5.1. Expert Visual-Based Health Risk Assessment System

The results of the experts' risk level assessments in different scenarios (random combinations of temperature, humidity, passenger flow, etc.) were exported from MYSQL, facilitating the quantitative study of subway microenvironmental health risks. The BP neural network, with its ability to synthesize complex relationships among multiple indicators and learn from data, objectively reflects the intrinsic connections between various indicators and health risks. Thus, we predicted the experts' risk results based on BP neural networks due to their suitability for analyzing the combined effects of numerous factors on subway microenvironmental health risks. The BP neural network calculates predicted outputs through forward propagation, computes errors at each layer, and then updates weights through error backpropagation until the error is minimized, achieving fitting to the training data [10]. Additionally, permutation feature importance provides a robust method for gaining insight into how the model makes predictions on a broad scale and is a common method to obtain indicator importance. Therefore, this study applied permutation feature importance to further analyze the expert samples. The core idea of permutation feature importance is to assess the impact of each feature on model predictions by permuting the features in the model and observing the change in model performance. Specifically, we built nonlinear relationships between indicators and risks using BP neural networks and explained the model to determine indicator importance through permutation feature importance.

Throughout the experiment, we iteratively adjusted the learning rate and the number of hidden layers and neurons to optimize the model's performance. One successful network structure consisted of 30 neurons in the input layer, four hidden layers with fourteen, nine, four, and five neurons, respectively, and five neurons in the output layer. This model was trained for 1000 iterations with a learning rate of 0.01, achieving remarkably high accuracy.

Figures 12 and 13 display the accuracy of the neural network's training and testing phases. Blue dots represent predictions that matched the actual results, while red dots represent predictions that did not match. As shown in Figure 12, the neural network model achieved an accuracy rate of 95.92% on the training set. Figure 13 illustrates that the model achieved an impressive test accuracy rate of 94.67%, indicating its strong predictive performance.

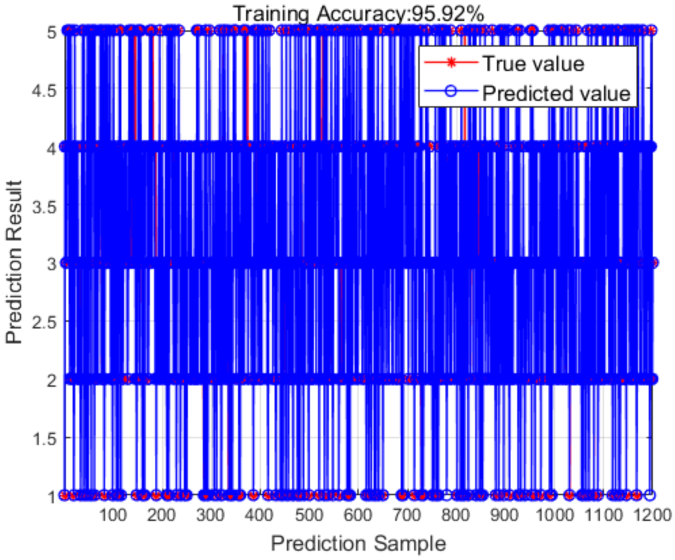


Figure 12. Prediction results of training.

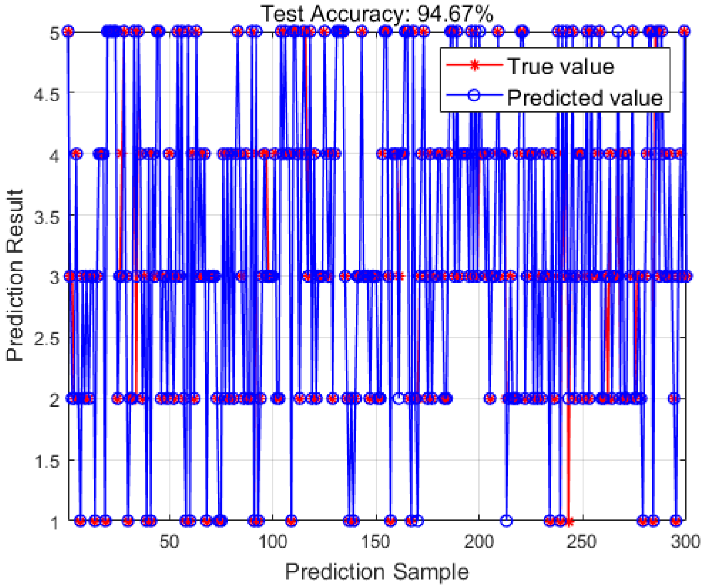


Figure 13. Prediction results of testing.

Next, each indicator was permutated 1000 times since the importance may have been unstable [10]. As shown in Figure 14, a deeper exploration of the importance for each indicator was demonstrated using box plots. The box plot in Figure 14 displays the distribution of the data, including the median, lower quartile, upper quartile, minimum, and maximum values. Subway microenvironmental health risks are influenced by the combined effects of multiple indicators, including key and secondary ones. Permuting important indicators can lead to significant fluctuations in intervention results, while permuting less important indicators has minimal impact. Figure 14 illustrates the fluctuation of indicator features based on their importance levels through feature permutation. As shown in Figure 14, indicators B1 and D1 were the most important, while C2 was the least important. This meant that the educational level and safety knowledge pass rate had the greatest influence on the health risk, while the emergency location pass rate had the least influence. This was conducive to comprehensive management of subway microenvironments health risks. Currently, the health risk control of subway operators is mainly guided by standard codes. But these codes are limited to identifying, for example, the threshold values and measurement methods of noise. The existing research on subway control measures also focuses on measures taken for certain factors, such as the development of intelligent ventilation control systems [95], dynamic gain timing ventilation control systems for subway internal ventilation, and magnetic hybrid filters for heavy metal pollution [96]. It was supposed that corresponding control measures should be taken whenever the factor exceeds the threshold, just like the physician treats the head when it aches, and treats the foot when it aches. However, in a complex subway microenvironment, several factors may exceed threshold values simultaneously. Leadership behaviors were crucial in this context [97]. For instance, if relatively unimportant indicators like C2, A3, and D5 exceed threshold values, subway operators may consider ignoring them if the overall underground microenvironmental health risk is acceptable. However, if important indicators such as B1, D1, A6, and A7 exceed threshold values, operators need to pay significant attention. Based on these results, subway operators can determine which factors should be prioritized and implement multimeasure controls to effectively manage excessive factors.

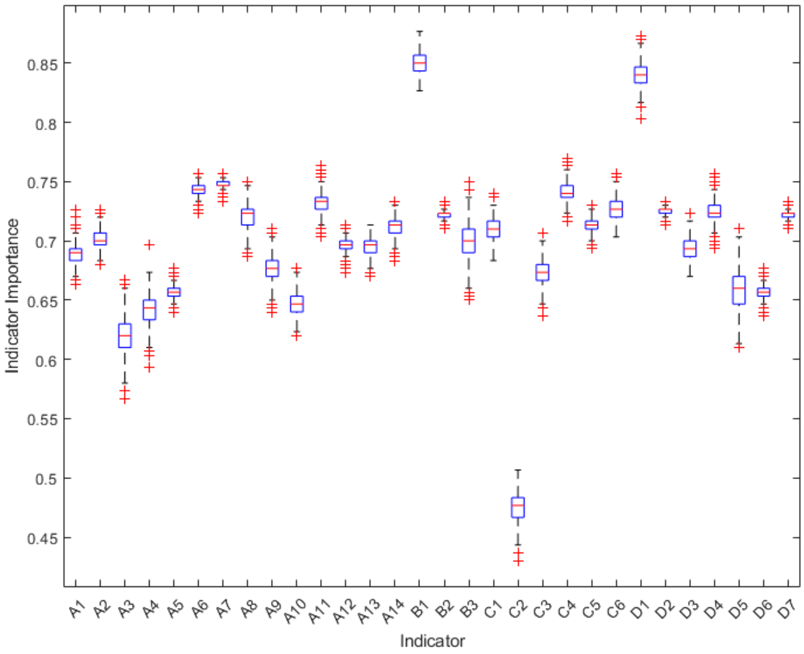


Figure 14. Indicator importance box chart.

In the future, the expert visual-based health risk assessment system could be combined with other approaches to further expand its functions, such as neural networks [98], particle swarm optimization [99], and genetic algorithms [100]. In addition, the hyperparameters of the predictive model could also be further optimized to achieve higher accuracy [101]. Moreover, the combination of an expert visual-based health risk assessment system, the Internet of Things (IoT), and Blockchain will optimize the importation of field data. When IoT is introduced, data such as the concentration of $PM_{2.5}$, humidity, and temperature, can be linked to the IoT by measuring instruments and importing data into the risk assessment system in real-time. The introduction of blockchain can ensure the reliability and security of data in the BIM-VR intelligent system [102]. The above two ideas to achieve functional expansion are not conflicting and it is suggested that these two ideas combined lead the direction of future research to realize the development of an intelligent and real-time expert visual-based health risk assessment system.

5.2. Passenger Risk Prevention Gamification Simulation System

The results from the passengers can also be exported from MYSQL, facilitating the quantitative study of the effectiveness of passenger training. Jaccard Similarity, a measure used to compare the similarity between samples, was calculated by determining the ratio of the intersection to the union of two sets. We calculated the Jaccard Similarity between the expert's standard answers and the passengers' answers, and plotted it as a scatter plot. As shown in Figure 15, the horizontal axis represents passengers, and the vertical axis represents similarity, with colors distinguishing different groups of experiments: blue for the initial round and red for the follow-up round after two days. The heights of the dots in Figure 15 indicate the Jaccard Similarity scores, where higher dots signify greater similarity. It should be noted that Jaccard Similarity values range from 0 to 1, where 0 indicates no overlap between the two sets and 1 indicates complete similarity. As seen in Figure 15, passengers' performance in the first round was relatively poor, with seven passengers scoring as low as 0%, highlighting their limited awareness of protection measures and weak risk coping capacity. However, the red dots, representing the follow-up round, were generally higher than the blue dots, demonstrating that the simulation system effectively improved passengers' awareness and encouraged them to take appropriate measures to reduce health risks.

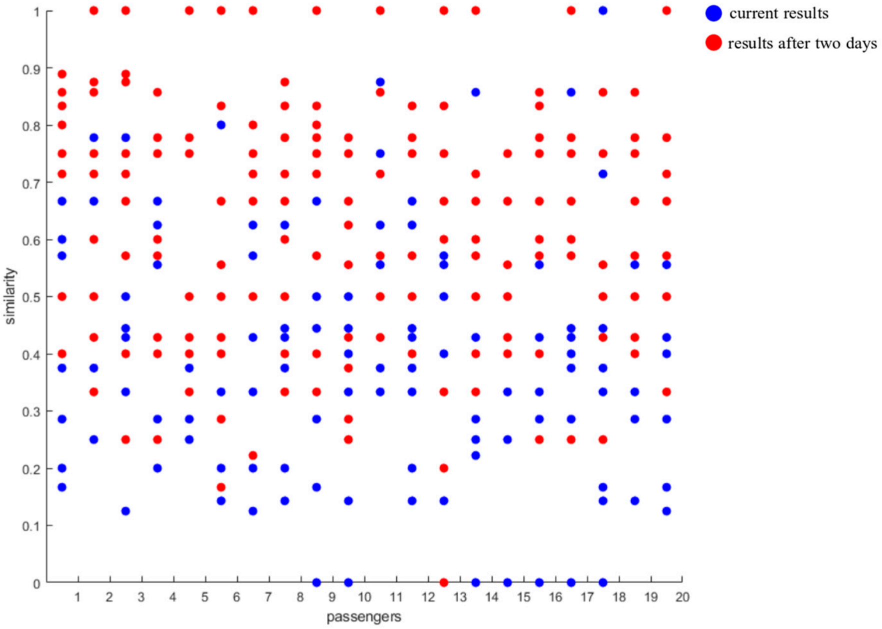
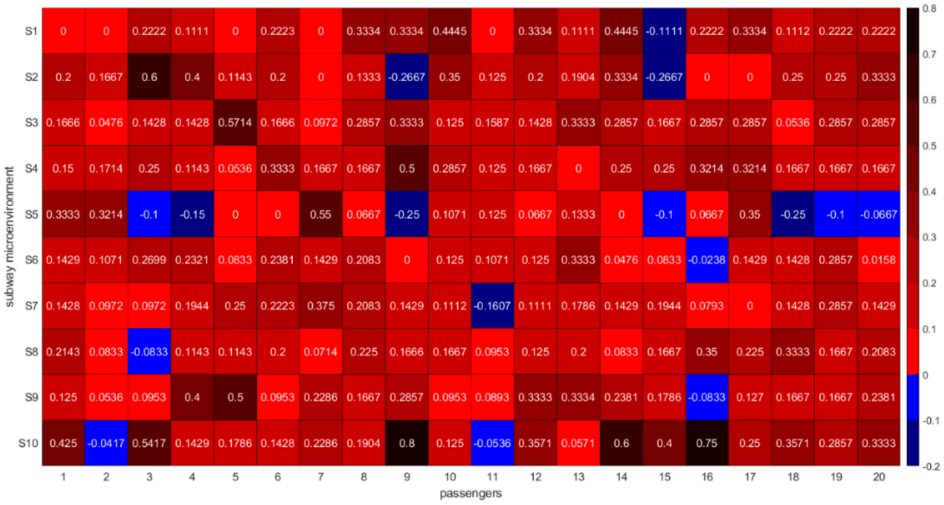


Figure 15. Similarity box chart.

Note: Redder colors represent an increase in similarity, while bluer colors represent a decrease in similarity. The numerical values represent the difference in similarity between the two rounds.

To better illustrate the improvement in similarity, we have depicted Figure 16. This study computed the similarity difference of each experimental subject. In Figure 16, redder colors indicate a greater increase in similarity, while bluer colors indicate a greater decrease. Additionally, the intensity of colors represents the magnitude of the values; deeper reds signify larger increases, while deeper blues signify larger decreases. The numerical values represent the difference in similarity between the two rounds. Overall, the trend showed that 92% of the region was in red, indicating a substantial increase in similarity. This further validated the fact that the passenger risk prevention gamification simulation system effectively enhanced passengers' risk coping capacity through continuous training.

While the study achieved good results, further in-depth analysis of passenger data is worth discussing. The system developed in this study, based on the extensive volume of passenger simulation results, can be integrated with data analysis software such as SPSS and Stata to delve deeper into population characteristics. This includes investigating whether passengers' coping behaviors vary based on factors like education level, age, gender, and occupation. Exploring these differences in characteristics can optimize the passenger risk prevention gamification simulation system. The system has the potential to incorporate more elements from passengers' perspectives in the future, simulating and training habitual behaviors. Moreover, we can categorize the population based on these characteristic differences and develop personalized passenger risk prevention gamification simulation systems for different categories of people. This approach would enhance the system's effectiveness by tailoring it to specific demographics and behaviors, ultimately improving passengers' risk coping capacities.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
S1	0	0	0.2222	0.1111	0	0.2223	0	0.3334	0.3334	0.4445	0	0.3334	0.1111	0.4445	-0.1111	0.2222	0.3334	0.1112	0.2222	0.2222
S2	0.2	0.1667	0.6	0.4	0.1143	0.2	0	0.1333	-0.2667	0.35	0.125	0.2	0.1904	0.3334	-0.2667	0	0	0.25	0.25	0.3333
S3	0.1666	0.0476	0.1428	0.1428	0.5714	0.1666	0.0972	0.2857	0.3333	0.125	0.1587	0.1428	0.3333	0.2857	0.1667	0.2857	0.2857	0.0536	0.2857	0.2857
S4	0.15	0.1714	0.25	0.1143	0.0536	0.3333	0.1667	0.1667	0.5	0.2857	0.125	0.1667	0	0.25	0.25	0.3214	0.3214	0.1667	0.1667	0.1667
S5	0.3333	0.3214	-0.1	-0.15	0	0	0.55	0.0667	-0.25	0.1071	0.125	0.0667	0.1333	0	-0.1	0.0667	0.35	-0.25	-0.1	-0.0667
S6	0.1429	0.1071	0.2699	0.2321	0.0833	0.2381	0.1429	0.2083	0	0.125	0.1071	0.125	0.3333	0.0476	0.0833	-0.0238	0.1429	0.1428	0.2857	0.0158
S7	0.1428	0.0972	0.0972	0.1944	0.25	0.2223	0.375	0.2083	0.1429	0.1112	-0.1607	0.1111	0.1786	0.1429	0.1944	0.0793	0	0.1428	0.2857	0.1429
S8	0.2143	0.0833	-0.0833	0.1143	0.1143	0.2	0.0714	0.225	0.1666	0.1667	0.0953	0.125	0.2	0.0833	0.1667	0.35	0.225	0.3333	0.1667	0.2083
S9	0.125	0.0536	0.0953	0.4	0.5	0.0953	0.2286	0.1667	0.2857	0.0953	0.0893	0.3333	0.3334	0.2381	0.1786	-0.0833	0.127	0.1667	0.1667	0.2381
S10	0.425	-0.0417	0.5417	0.1429	0.1786	0.1428	0.2286	0.1904	0.8	0.125	-0.0536	0.3571	0.0571	0.6	0.4	0.75	0.25	0.3571	0.2857	0.3333

Figure 16. Passenger similarity difference heat map.

5.3. *Results of Subject Evaluation with Questionnaire Surveys*

Apart from the quantitative analysis of expert and passenger results, we designed a simulated feedback questionnaire based on references of Zhang et al. (2023) [103]. After each participant completed the entire 4.2 virtual simulation, they sat quietly in the laboratory for 10 min as a buffer period. Then, we invited the participants to rate our system based on their experimental experience using a five-point Likert scale. All participants provided their feedback and rated the system on a 5-Point Likert Scale after the entire test was completed. In this scale, 1 represents strongly disagree, and 5 represents strongly agree. The questionnaire data are summarized in Table 5.

Table 5. Results of the five-point Likert questionnaire evaluation.

Question	Average Scores of Experts	Average Scores of Passengers
1. The simulation system is helpful.	3.75	3.65
2. The virtual environment is in line with reality.	4.15	3.8
3. The logistic of actions in VR is in line with reality.	3.75	4.15
4. The instructions for roaming and collecting indicator are easy to follow.	3.5	3.75
5. I can get a better understanding of subway microenvironmental health risks.	3.55	3.95
6. I feel fairly comfortable when using the system, e.g., no dizziness.	3.25	3.1
7. The system provides better visualization for better understanding.	3.7	3.9
8. I am more confident to copy with risks easily and correctly through repeated training. (only for passengers)	-	3.65

Based on the scores, the overall system performance was satisfactory. The simulation system received positive feedback from both experts and passengers, indicating an improved understanding of subway microenvironmental health risks. Additionally, the majority of passengers expressed confidence in their ability to handle microenvironmental health risks better through repeated training.

6. Discussion

In the field of architecture, building information modeling (BIM) stands out as a widely embraced modeling tool among engineers, often described as "a digital representation of physical and functional characteristics of a facility" due to its robust modeling capabilities. BIM serves as both a tool and a concept that evolves with advancing technological trends [104]. However, it is crucial to note that BIM's primary application has traditionally been during the design or construction phases, focusing on tasks like cost control and clash detection. For instance, Li et al. (2020) introduced a budget control method for port construction projects leveraging BIM technology to alleviate practical economic pressures and establish effective cost control environments [105]. Similarly, Luo et al. (2022) employed BIM to create a sustainable multidisciplinary evaluation framework for subway pipeline clash detection and analysis [106]. Despite its extensive use, the architecture field has long advocated for comprehensive lifecycle management, underscoring the importance of safety and smooth operation during the operational phase [107]. However, the value of BIM during this phase has not been thoroughly explored. Therefore, this study pioneers the application of BIM in the operational phase of large-scale infrastructure projects, aiming to broaden the scope of BIM utilization throughout the entire project lifecycle.

Furthermore, when evaluating the environmental health of large-scale infrastructure like subway stations, sluices, dams, and high-speed rail stations, conventional methods typically involve questionnaires and field tests [108–110]. For example, Lee et al. (2018) utilized a thermal-optical elemental analyzer and an organic carbon analyzer to measure particulate matter in subway environments [111]. However, the time-consuming nature of field tests has been a longstanding concern in academia. Therefore, questionnaires that can be completed in the short term are commonly used for environmental risk assessments. For instance, Yang et al. (2022) conducted thermal comfort surveys in the Harbin subway in China [12]. Moreover, Han et al. (2015) conducted surveys based on five dimensions: heat, air, light, sound, and overall comfort [35]. Our research methodology was inspired by the work of Wu et al. (2011) and Nie (2020) [112,113]. In the former's study, questionnaires were used for strategic environmental assessment, but the scholars noted that the data collected from questionnaires was often incomplete and insufficient. Similarly, in our study, without the use of virtual technology, the scenarios for expert risk assessment and passenger training would be limited, as extreme subway microenvironments are rarely encountered in real-life situations. In Nie's study (2020), marine architecture in coastal cities was designed using "BIM plus VR", which compensated for the limitations of traditional architectural design methods through features like visibility, optimization, and simulation. Therefore, drawing inspiration from Nie (2020) [113], our study aimed to address the limitations of questionnaires and field tests in environmental assessment by integrating BIM and VR technologies. This integration allows experts to conduct subway microenvironment assessments efficiently and comprehensively, enhancing the overall quality and depth of the assessment process.

Additionally, for training related to large-scale infrastructure, passengers typically rely on methods such as field exercises, video watching, and brochures to enhance their coping capacity. However, the audience for field exercises was limited, and the effectiveness of methods like video watching and brochure reading was often constrained. Our research drew inspiration from Rajabi et al. (2022) [114], who utilized VR technology to design and model a virtual scenario evaluating the impact of education and anticipation on residents' decision-making under earthquake stress conditions. VR's visual effects are often more engaging and appealing to passengers. This study aimed to depart from traditional methods by leveraging VR technology to enhance the coping capacity of subway passengers. Previously, the advantages of VR in providing immersive and engaging virtual environments have been extensively utilized by Van and De (2009) and Wang et al. (2018) for specialized training of healthcare workers, mining workers, and construction practitioners [115,116]. It has been demonstrated that VR training can significantly improve safety awareness and behavioral capacity among users [117,118]. This study further confirmed these findings, highlighting the significant potential of VR for behavioral training purposes.

In conclusion, this study contributed significantly from both practical and academic perspectives. Practically, our research has revolutionized traditional subway risk management by introducing intelligent systems that provide immersive experiences of subway microenvironments for experts and passengers. These systems offer innovative models for environmental assessment and passenger training, aiding subway operators and researchers efficiently collecting comprehensive subway environmental data and policymakers in informing government policies on subway environmental management. This is highly beneficial for managing complex projects [119]. From an academic viewpoint, this study fostered interdisciplinary integration among urban planning, environmental science, and technology development. By integrating various software tools like Revit, Navisworks, Unity, MYSQL, and Visual Studio, we comprehensively simulated subway infrastructure microenvironmental conditions. Moreover, it expanded the application scope of BIM technology, leveraging it to play a more extensive role throughout the entire lifecycle of construction projects. The intelligent systems play a pioneering and foundational role in ensuring the healthy and safe operation of public transportation.

Nonetheless, it is important to acknowledge the limitations of this study. Firstly, although VR devices have been improved, from desktop 3D graphics to head-mounted devices (e.g., HMDs) and VR glasses (e.g., Oculus Rift), they can rarely achieve the simulation of all senses (touch, hearing, sight, taste, and smell). Due to the limitation of this technology, only the sense of sight is realized in the systems. It is encouraged to use more advanced devices in the near future to achieve immersive sensory experiences encompassing vision, hearing, touch, and smell such as sEMG wearable sensors [120]. Additionally, it must be acknowledged that due to psychological and experiential differences in VR simulations, there may be discrepancies between the results obtained from case studies and actual values. Therefore, in future research, it is advisable to conduct standardized psychological tests and VR simulation training before VR simulation to reduce the probability of experts and passengers making erroneous judgments due to psychological stress. Lastly, due to resource constraints, the case study in this research only involved 20 passengers and 20 experts, making it inadequate to test intelligent systems on a wide range of people. It is suggested to expand the scope of validation in future research to include individuals of different ages and educational backgrounds, thus broadly verifying the practicality and effectiveness of the intelligent systems. At the same time, we also hope that complex guidelines could be simplified, making BIM-VR applications more accessible to urban planners and civil engineers [121].

7. Conclusions

Subway microenvironmental risks pose a significant threat to the health of passengers. However, few intelligent systems are proposed to facilitate the management of subway environments. This study proposed novel intelligent systems for enhancing subway environment management. Based on different application functions, the systems included an expert visual-based health risk assessment system and a passenger risk prevention gamification simulation system. It also validated the feasibility by using the Xinzhuang Station in Nanjing Subway Line 3 as the case study. The case study results demonstrate that the intelligent systems developed in this study are viable. Additionally, with the assistance of a passenger risk prevention gamification simulation system, the passengers' coping capacity was greatly enhanced. The feedback questionnaire further affirmed the value of the intelligent systems.

This study has significantly advanced interdisciplinary integration among urban planning, environmental science, and technology development. It combined various software tools like Revit, Navisworks, Unity, MYSQL, and Visual Studio to comprehensively simulate the subway infrastructure's microenvironmental conditions. This has expanded BIM technology's application scope, empowering it to play a more extensive role across construction project lifecycles. Practically, the intelligent systems proposed offer innovative models for environmental assessment and passenger training, benefiting subway operators and researchers in data collection and government authorities in policy formulation. While this study focused on subway microenvironmental health risks, its framework is adaptable to various research objects like public buildings (office buildings, shopping malls, hotels, libraries, airports, etc.,) residential buildings, and industrial structures. Furthermore, there is potential for integrating different virtual technologies like AR, VR, MR, etc., with BIM and traditional architectural software to create more intelligent systems with improved information exchange and sensory realism.

Author Contributions: Conceptualization, Q.C. and P.M.; methodology, Q.C. and C.L.; software, Q.C. and C.L.; validation, X.X., Q.C. and C.L.; formal analysis, Q.C. and C.L.; resources, X.X. and P.M.; data curation, X.X. and L.X.; writing—original draft preparation, Q.C.; writing—review and editing, L.X., X.X. and P.M.; visualization, L.X.; supervision, X.X. and P.M.; project administration, L.X. and X.X.; funding acquisition, X.X. and P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (72071115), Nanjing Medical Science and Technology Development Fund (ZKX21053) and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (SJCX22_0302).

Data Availability Statement: The data from this article can be found online at https://github.com/Qiwenchen12/BIM-VR.git (accessed on 5 May 2024).

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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