Digital twin for multi-scenario emergency of railway passenger stations

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Emergency disposal is a critical aspect for railway stations to ensure safety. This requires the implementation of emergency plan simulations and cost-effective immersive drills. In the paper, we incorporate a set of disposals for events into emergency processes and model the personnel, supplies, and equipment to create multiple emergency scenarios. Additionally, we introduce a digital twin-based solution for multiple scenarios of emergencies. This solution completely restores the key components of a station in the information space and provides an immersive way for emergency disposals. The four-dimensional model used in the solution simulates and interacts with the station, and it is composed of the details of passenger station physical entity, multi-scenario emergency virtual entity, digital twin connection, and emergency twin service. The digital twin for versatile emergency events such as fire disaster, natural disaster (e.g., flood, earthquake), social security incident, and public health event have been constructed using the model. The solution was tested at Qinghe, a station during Beijing-Zhangjiakou high-speed railway in China. By utilizing the actual operation data of Qinghe, we validated the multi-scenario emergency drills, simulated the corresponding emergency disposal plans, and assessed the proposed solution from three aspects: the fidelity of the real-world simulation, coverage of the multiple emergency scenarios, and the user-friendliness. The evaluations indicate that the proposed solution attains *good* score and the *acceptable* level of system usability scale.

1 Introduction

In China, the safety of passengers who board and alight at train stations is of utmost importance. Emergency events [1] such as fire disaster, natural disaster, public health event, and social security incident directly threaten the passengers' lives and property. According to regulations [2,3], station staff address these issues through emergency measures that comprise regular drills and validation of plans during emergencies. Existing emergency drill uses either tabletop exercises or live drills to enhance response capabilities, but they both have limitations. Tabletop exercises lack an immersive experience, while live drills waste resources and are limited in simulating multiple potential hazards. Additionally, management cannot ascertain the effectiveness of response plans during emergencies, nor assess their scientific validity. Recently, the

research [4] proposes to use IoT for Railway Emergency Detection and Response System. In China, currently the Intelligent Railway Passenger Station (IRPS) [5] system is used to enable real-time tracking of emergency processes and develop emergency drill plan for staff. Additionally, research has focused on railway 3-dimensional (3D) exercises, providing staff with single-scenario training [6,7]. To provide staff with a method to instantly validate emergency plans and offer immersive training in multiple disaster scenarios, we introduce digital twin technology. By replicating the real-world scenarios in a virtual environment and using actual data from station personnel, equipment, trains, passengers, and the environment, we enable the simulation of emergency processes and immersive training for various disaster events. The primary contributions of this paper can be summarized as follows.

- This study builds upon existing station emergency management protocols to meticulously construct a comprehensive outline of multi-emergency scenario, including fire, natural disaster (such as flood, earthquake), social security incident, and public health event. This outline provides a systematic approach to analyze and manage these situations.
- In analyzing emergency disposal process, this paper employs the Generalized Stochastic Petri Net (GSPN) [8] model. We have transformed each step of the response process into places, tokens, and transitions within the GSPN. The model calculates the duration of each transition through parallel, branching, and sequential structures. GSPN is then formulated as a Markov chain. It enables the study to identify weaknesses in the emergency disposal process, providing a basis for personnel adjustments.
- This research successfully integrates digital twin technology into emergency management. In this paper, we use a Digital Twin-Based model for Multi-Scenario Emergency (ED4D) to provide a detailed description of the process, which will furnish digital twin for process entities, facilitate interfaces to interact with reality, and offer services to manage emergency events. This model consists of the Passenger Station Physical Entity, Multi-Scenario Emergency Virtual Entity, Digital Twin Connections and Emergency Twin Services. By replicating the actual situation of the physical world in a virtual environment in real time, we allow the information exchange between both spaces. The characteristics facilitates the deduction of emergency processes and immersive drills for various disaster events.
- The ED4D model was validated at Qinghe Station, encompassing fire disasters, natural disaster (e.g., flood, earthquake), social security incidents, and public health events. By utilizing actual operational data from Qinghe Station (such as passenger numbers, staff, emergency resources, equipment status) through digital twin connections, we confirmed the effectiveness of the solution. This enables us to simulate emergency processes and conduct more efficient emergency drills.

2 Related works

2.1 Modeling techniques for emergency process

There are numerous tools proposed for modeling the common business process, such as the conditional directed graph [9], extended event-driven process Chain [10], Petri Net [8,11], and Integrated Computer Aided Manufacturing [12]. Among these methods, Petri Net and its extension have the strongest ability to explain the stochastic nature of events in business process. As a result, they are well-suited for representing random events that occur with a certain probability in business processes. Petri Net has gained extensive usage in the modeling of processes across diverse fields. In the context of emergency processes, they have found application in modeling emergency decision-making [13], scenario evolution of mass emergency events [14], emergency response to flood [15], and emergency capability assessment of meteorological disasters [16]. In the field of railway processes, Petri Net has been employed in the modeling of customs clearance analysis of the China-Laos railway [17], emergency dispatching and cooperative disposal of high-speed railways [18], emergency evacuation of complex passenger flow in railway passenger stations [19], as well as safety assessment and risk control [20].

2.2 Digital twin technology

The concept of the digital twin, as referenced in [21], involves creating a replica of the physical world in a digital space. This allows for the exchange of data between the two realms. By connecting with real-world entities, it is able to gather real-time data on the current state of affairs, mimic real-life situations, simulate operational scenarios, make intelligent decisions, and relay this information back to the existing system for control interaction. This technology has found its way into various fields such as industry [22–24], culture [25,26], medicine [27–29], construction [30]; [31], and intelligent maritime transportation [32]. In the railway operation industry, digital twin technology can be leveraged to merge different data sources and models for monitoring [33], turnout management [34], diagnostics [35], and prognostics [36]. It has the advantages of acquiring the actual state, mirroring the real situation, simulating the operation scenario, making generation-assisted decisions, and realizing control interaction.

2.3 Emergency drill based on 3D technology

The advancement of computer technology has facilitated the integration of 3D technology in skill training programs, including automobile maintenance training [37], railway axle disc brake maintenance [38], tunnel fire emergency drills [39], ship fire emergency drills [40], railway workers' skill training [41], and train crew management [42]. The use of 3D technology enables the creation of a natural world in the information space that dynamically simulates disaster occurrences with negative outcomes, such as damages, losses, injuries, and fatalities. This

technology resolves the challenge of large resource consumption and enhances the sense of immersion.

2.4 Systems usability evaluation

User evaluation is a common approach to determine whether a software application is meeting its intended usage requirements. The system usability scale (SUS) [43] is a widely accepted questionnaire standard that consists of ten questions designed to assess usability. The after-scenario questionnaire [44] is composed of three questions that evaluate time, difficulty, and information support. The usability metric for user experience [45] is a rating system that involves four questions covering three dimensions: usefulness, efficiency, and satisfaction. The Happiness-Engagement-Adoption- Retention-Task Success (HEAR) framework [46] is an evaluation tool used for internal enterprise software applications, which assesses the time required to complete tasks and their level of difficulty.

3 The modeling of multi-scenario emergency

Multi-Scenario Emergency is a comprehensive framework that encompasses various types of emergency situations. A scenario, which is a delineation of emergency events, serves as the impetus for emergency response procedures and the mobilization of resources by personnel to execute a series of disposal actions aimed at mitigating and controlling the escalation of the situation. There are several types of emergencies in the station, categorized into four groups[1]: fire disaster, natural disaster, social security incident, and public health event. In the paper, we focus on five events for Multi-Scenario Emergency: fire, flood, earthquake, social security incident, and public health event. Although the fundamental process of emergency disposal remains constant for different events, the disposal personnel, resources and tasks differ. This paper provide a detailed outline of the disposal scenes for various emergency events in Section 3.1 and present a GSPN to describe the process of emergency disposal in Section 3.2, thereby defining a multi-scenario emergency disposal model.

3.1 Multiple emergency scenarios

Scenarios consist of a combination of events, equipment, personnel, resources, and individual actions. In accordance with the chronological progression of events, personnel execute a series of action measures to steer the events towards the intended outcome. In relation to transportation stations confronted with circumstances such as fire, flood, earthquake, social security incident, and public health event, we have undertaken an evaluation of emergency procedures, outlining personnel requirements, resource allocation, equipment utilization, and disposal methodologies. The specifics are presented as follows.

- **Fire disaster.** In the occurrence of a fire alarm signal, the passenger station is responsible for taking prompt measures to guarantee the security of its passengers. The primary action involves reporting the occurrence to the station manager, who will evaluate the extent of the incident and determine whether to initiate the emergency response plan. Pursuant to the plan, station employees must conduct various tasks, including consoling passengers, safely evacuating them, contacting local rescue services for aid, utilizing firefighting equipment, and extinguishing the fire. After the fire has been contained, the site must be restored, and a post-event summary should be created to evaluate the efficiency of the emergency response.

- **Natural disaster.** Upon receipt of an earthquake or severe weather alarm, the station manager initiates an assessment of the situation to determine the appropriate emergency response level. Subsequently, in compliance with the emergency plan's provisions, the station staff undertakes emergency tasks, including passenger reassurance, passenger evacuation, itinerary modifications, coordination with local rescue teams, acquisition of emergency resources, on-site rescue operations, and other related duties. Post-disaster, the site is restored to its previous state, and the emergency is concluded upon completion of the restoration process.

- **Social security incident.** Upon discovery of violent acts at the train stations, the staff promptly notifies and reports to the station manager. The manager evaluates the situation and implements the emergency response plan in accordance with established guidelines. The staff carries out emergency duties such as passenger evacuation, coordination with the police department, and on-site rescue operations. Once the offenders are apprehended, the site is restored to its original state. Ultimately, a post-incident analysis is performed.

- **Public health event.** When a case that is suspected to involve a contagious disease is reported, the station without delay informs the station manager for evaluation. Depending on the assessment, the station personnel are required to undertake several emergency tasks, which include, but are not limited to, providing reassurance to passengers, ensuring their safe evacuation, reaching out to the local disease control department, implementing on-site isolation measures, and more. Once all the individuals suspected of carrying the disease have been transported, the site must be restored to its original state, and a post-incident review must be carried out to determine the effectiveness of the response and identify areas for improvement.

To provide a succinct overview, the alarm circumstances exhibit a range of fluctuations in accordance with the emergency situations. In the course of these situations, personnel undertake assorted duties, necessitate a diverse array of external rescue measures, and obtain access to a variety of emergency resources. The specifics pertaining to these factors are concisely encapsulated in Table 1.

TABLE 1 Unique entity details for each scenario emergency of station.

Class	Fire disaster	Natural disaster	Social security incident	Public health event
Aid workers	doctors, firemen	ministry of emergency management, doctors, firemen, policemen	policemen	Staffers of Government epidemic prevention department, doctors
equipment and facilities (*EQU*)	Fire extinguisher, fire hydrant, spray, blister, curtain door, smoke alarm	Pump and emergency light	blasting protection	Disinfection sprayers, isolation belts, protective articles[1]

FIGURE 1
The common process of the emergency disposal.
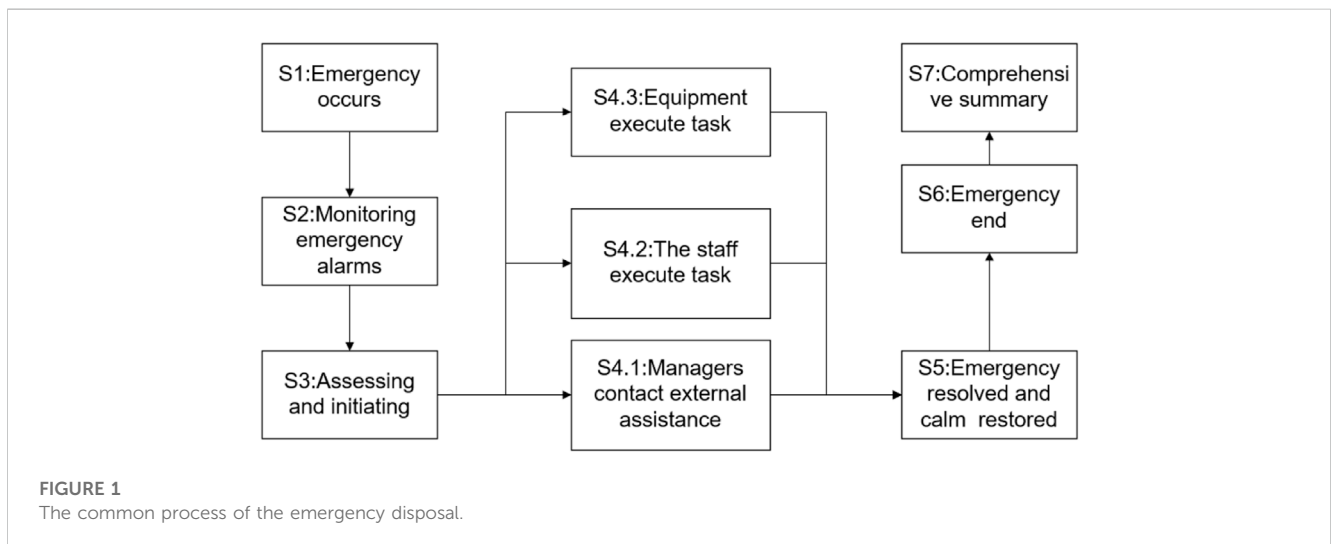
3.2 The GSPN model for multi-scenario emergence processes

A strategy for managing various emergency situations is established as a common disposal protocol, as depicted in Figure 1. The procedure is initiated by monitoring emergency alarms and determining their seriousness level, as illustrated by S1, S2 and S3 in Figure 1. During an emergency, the station activates multiple staff members to participate in the disposal effort, as exemplified by S4.1, S4.2 and S4.3 in Figure 1. Once the situation has been resolved and the site has been restored, the emergency will be concluded, followed by a comprehensive summary of the emergency process, as illustrated by S5, S6 and S7 in Figure 1. The aforementioned process can be represented as a sequence S1 and S2 as shown in Figure 1, branching S3 and S4 as depicted in Figure 1, and parallel parts S4.1, S4.2 and S4.3 as illustrated in Figure 1. These components can be effectively portrayed by using a Petri Net [8,11].

Petri Net [8,11], a graphical mathematical modeling tool, is comprised of four essential components: place, transition, token, and directed arc. Place represents the current state of the system, transition signifies state changes, and token represents system resources. Directed arc, on the other hand, illustrates the relationship between Place and transition while also indicating the direction of token flow. However, Petri Net is not equipped to handle cases where the transition is a random delay, and the state space grows exponentially with the increase of the problem. The GSPN addresses this issue [18,47,48]. The introduction of time

values and random numbers in GSPN enhances Petri net, allowing for the modeling of features such as random delay, variable time, and randomness. Therefore, we adopt it to model the comprehensive emergency process. As the emergency process proceeds, tasks must be continuously adapted to site conditions, and each task may require varying amounts of time to complete.

The GSPN for emergencies disposal [15] is a directed graph described by eight elements:

$$GSPN^i = (P, T, F, W, M, \lambda, PIT, BT) \tag{1}$$

Here, the raised index i is used to differentiate a variety of emergency occurrences and assumes values from a set of {1, 2, 3, 4, 5}. Specifically, 1 represents fire, 2 flood, 3 earthquake, 4 social security incident, and 5 public health event. The meaning of the eight constituents is outlined as follows.

- P denotes a finite collection of *places* that serve as a container for tokens. In this article, the term *Place* specifically refers to different sets of information, while *token* denotes specific pieces of information.
- T represents a finite assortment of *transitions* that bring about changes in emergency situations.
- F comprises the set of *directed arcs* that establish a connection between P and T.
- W is the collection of arc weights that specify the maximum number of tokens that can traverse each arc.
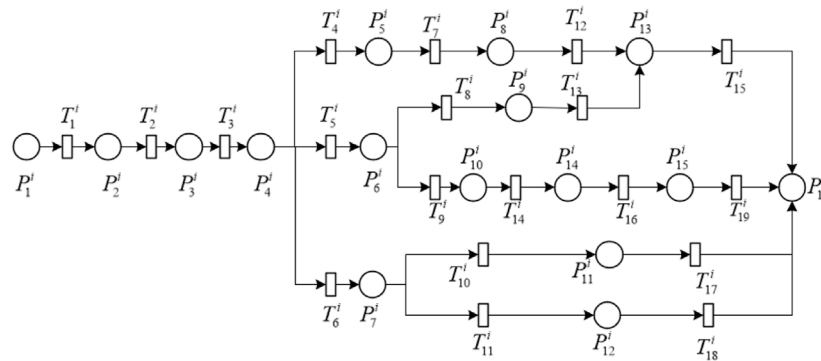- M serves as a status flag, representing the quantity of tokens within each P, for each state.

FIGURE 2
The GSPN of the emergency disposal.

- λ is associated with the *occurrence probability*. Upon fulfillment of specific conditions, the related transitions occur; the occurrence of the transition is independent of each other. λ then parametrizes the distribution function for the occurrence.
- *PIT* signifies the moment when the transition undergoes a change, represented by $\{Time_i\}$.
- *BT* keeps track of the time delay for each transition in *T*.

The entire process, beginning with monitoring and ending with the emergency summary, is modeled by GSPN, which encompasses all stages, as indicated in Figure 2. The GSPN model is made up of 16 place and 19 transitions, which effectively represent all crucial aspects of the emergency process within a restricted set. Further information regarding *P*, *T*, *PIT*, *BT* is available in Table 2.

The initial data set P_1 is made available at $Time0$, and the values of $Time_i$ are derived using Eq. 2. Through calculations, we can establish the corresponding point-in-time for every P_k, which in turn allows us to make an estimate of the total time required for the emergency process. As illustrated in Figure 2, the time for P_8 is determined by the leading P_5 as the start time, plus the duration needed to execute T_7. The start time of P_{13}, is determined as the maximum of two sums; one is the sum of the start time of P_8 plus the duration needed to execute T_{12}, and the other is the start time of P_9 plus the duration needed to execute T_{13}. The P_{13} can only start after the completion of both branches.

The transfer of the token from one *P* to another signifies a shift in the system's state. We set the flag for token changes in GSPN as denoted by vector set *M* in Eq. 3. The magnitude of vector M_i corresponds to the quantity of *P*. Each element in the vector M_i represents the quantity of tokens present in the *P* [49]. In the paper, the *M* is comprised of a set of 15 vectors, and each vector has 16 elements, as depicted in Eq. 3.

The model's initial sign is M_1, upon the occurrence of a token in P_1 that means the events occur alarm information, the transition T_1 is triggered with probability λ_1 and the token is transferred to P_2. The transition T_1 requires BT_1 time units and results in a change from M_1 to M_2, as depicted by the sequence shown in Figure 1 S1 to S2. In this moment, the token is in P_2 and the status is M_2 as Eq. 3, which means the event status exceeds the safety threshold. Similarly, the fourth status change is indicated by M_4, where P_4 possesses a token

and signifies the current state of emergency disposal plan determination.

$$\begin{cases} Time1 + BT_1 = Time2 \\ Time2 + BT_2 = Time3 \\ Time3 + BT_3 = Time4 \\ Time4 + BT_4 = Time5 \\ Time4 + BT_5 = Time6 \\ Time4 + BT_6 = Time7 \\ Time5 + BT_7 = Time8 \\ Time6 + BT_8 = Time9 \\ Time6 + BT_9 = Time10 \\ Time7 + BT_{10} = Time11 \\ Time7 + BT_{11} = Time12 \\ max(Time8 + BT_{12}, Time9 + BT_{13}) = Time13 \\ Time10 + BT_{14} = Time14 \\ Time14 + BT_{16} = Time15 \\ max(Time13 + BT_{15}, Time15 + BT_{19}, Time11 + BT_{17}, Time12 + BT_{18}) = Time16 \end{cases}$$
(2)

Subsequently, the token in P_4 split into three, as depicted by the branching shown in Figure 1 (S3 to S4), transitioning the status from M_4 to M_5. The transition T_4 describes one token changes from P_4 to P_5, which represents the assistance seeking from Aid workers. The transition T_5 describes other token changes from P_4 to P_6, which denote staff task reception. The transition T_6 describes another token changes from P_4 to P_7, which indicate station equipment task reception. M_5 corresponds to the fifth state change, with P_5, P_6, and P_7 containing one token each as Eq. 3, and the parallel shown in Figure 1 (S4.1, S4.2 and S4.3).

$$\begin{cases} M_1 = (1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0) \\ M_2 = (0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0) \\ M_3 = (0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0) \\ M_4 = (0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0) \\ M_5 = (0,0,0,0,1,1,1,0,0,0,0,0,0,0,0,0) \\ M_6 = (0,0,0,0,0,1,1,1,0,0,0,0,0,0,0,0) \\ M_7 = (0,0,0,0,1,0,1,0,1,1,0,0,0,0,0,0) \\ M_8 = (0,0,0,0,1,1,0,0,0,0,1,1,0,0,0,0) \\ M_9 = (0,0,0,0,0,0,1,1,1,1,0,0,0,0,0,0) \\ M_{10} = (0,0,0,0,1,0,0,0,1,1,1,1,0,0,0,0) \\ M_{11} = (0,0,0,0,0,0,0,1,1,1,1,1,0,0,0,0) \\ M_{12} = (0,0,0,0,0,0,0,1,1,0,1,1,0,1,0,0) \\ M_{13} = (0,0,0,0,0,0,0,1,1,0,1,1,0,0,1,0) \\ M_{14} = (0,0,0,0,0,0,0,0,0,0,1,1,1,0,1,0) \\ M_{15} = (0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1) \end{cases}$$
(3)

TABLE 2 P (Place), PIT, T (Transition) and delay meanings.

P(Place)	Meaning	PIT	T (Transition)	Meaning	Delay
P_1	Alarm information of the events occur	Time1	T_1	The event impact is increasing	BT_1
P_2	Alarm information of the event status exceeds the safety threshold	Time2	T_2	Disaster evaluation and emergency disposal are beginning	BT_2
P_3	Emergency information on disaster assessment and activation	Time3	T_3	The emergency response plan and problem are being generated	BT_3
P_4	Emergency solution information	Time4	T_4	Staff is seeking assistance from aid workers	BT_4
P_5	Information of Aid workers arrived station	Time5	T_5	Staff members are receiving the assigned tasks	BT_5
P_6	Information of station staff on site	Time6	T_6	The station equipment is receiving the assigned	BT_6
P_7	Information of Station equipment receives task feedback	Time7	T_7	Aid workers are developing rescue plans	BT_7
P_8[a]	Information of Aid workers feedback	Time8	T_8	Staff is guiding passengers with the evacuation process	BT_8
P_9	Feedback information of station staffers guided passengers evacuation	Time9	T_9	The staff is working on duty	BT_9
P_{10}	Feedback information of station staff execute task	Time10	T_{10}	The station equipment is executing commands	BT_{10}
P_{11}[b]	Information of station equipment finish tasks	Time11	T_{11}	The evacuation device is executing commands	BT_{11}
P_{12}	Information of evacuation devices finish tasks	Time12	T_{12}	Aid workers are implementing rescue plans	BT_{12}
P_{13}	Information of passenger safety	Time13	T_{13}	The passengers are completing the evacuation process and arriving at a safe location	BT_{13}
P_{14}	Feedback information of staff obtain emergency resource	Time14	T_{14}	The staff is acquiring emergency resources and executing tasks	BT_{14}
P_{15}	Feedback information of staff finish tasks	Time15	T_{15}	The staff is checking the safety status of the passengers	BT_{15}
P_{16}	Information of emergency disposal end	Time16	T_{16}	Staff is executing tasks by utilizing emergency resources	BT_{16}
-	-	-	T_{17}	The staff is inspecting the equipment to ensure completion of tasks	BT_{17}
-	-	-	T_{18}	The staff is inspecting the evacuation devices to ensure completion of tasks	BT_{18}
-	-	-	T_{19}	The staff is verifying the completion of field tasks	BT_{19}

[a] P_8 in GSPNa represents firemen; P_8 in GSPNb represents government; P_8 in GSPN3 represents government; P_8 in GSPN4 represents policemen; P_8 in GSPN5 represents doctors.
[b] P_{11} in GSPNa represents extinguisher, fire water monitor, loudspeaker, guide screen, and evacuation equipment; P_{11} in GSPNb represents pump, loudspeaker, guide screen and evacuation equipment; P_{11} in GSPN3 represents emergency light, loudspeaker, guide screen and evacuation equipment; P_{11} in GSPN4 represents explosion-proof blanket, loudspeaker, guide screen and evacuation equipment; P_{11} in GSPN5 represents isolation belt, Sterilizing instrument, loudspeaker, guide screen and evacuation equipment.

In GSPN, token transitions exhibit a certain degree of randomness. Given that the Markov chain is a type of stochastic process, GSPN can be effectively analyzed for system stability using Markov chain methods. GSPN having a finite number of places and tokens are equivalent to a one-dimensional continuous-time Markov chain model [49]. To gain a comprehensive grasp of the entire emergency process, we utilize Markov chain to analyze potential weaknesses. We can obtain Markov chain that are isomorphic to the simplified GSPN model, as shown in Figure 3. The Markov chain is obtained by using the probability occurrence λ_k of the triggered transitions as the directed edge. In branching scenarios, different states are generated due to varying branch duration. Branching starts from P_4, resulting in multiple states corresponding to M_5 and its subsequent transitions. During the transition from M_5 to M_6, M_7, and M_8, due to different branch times for P_5, P_6, and P_7, there is a probability λ_5 that P_5 has completed while P_6 and P_7 remains incomplete, as M_6. The same applies to the
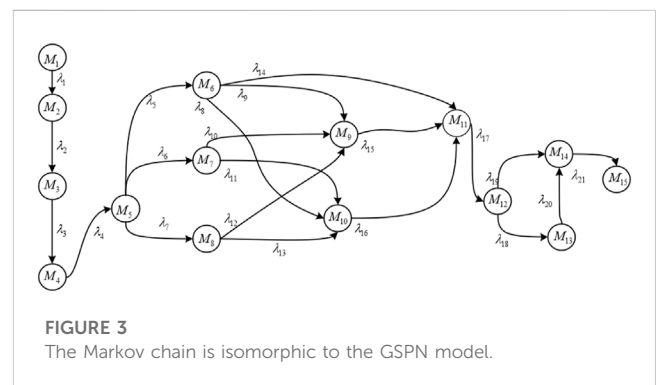

FIGURE 3
The Markov chain is isomorphic to the GSPN model.

generation of M_7 and M_8. After the completion of P_5 and P_6, M_9 is generated, and after the completion of P_6 and P_7, M_{10} is generated. Therefore, from M_6, M_7, and M_8, we can reach both M_9 and M_{10}. M_9
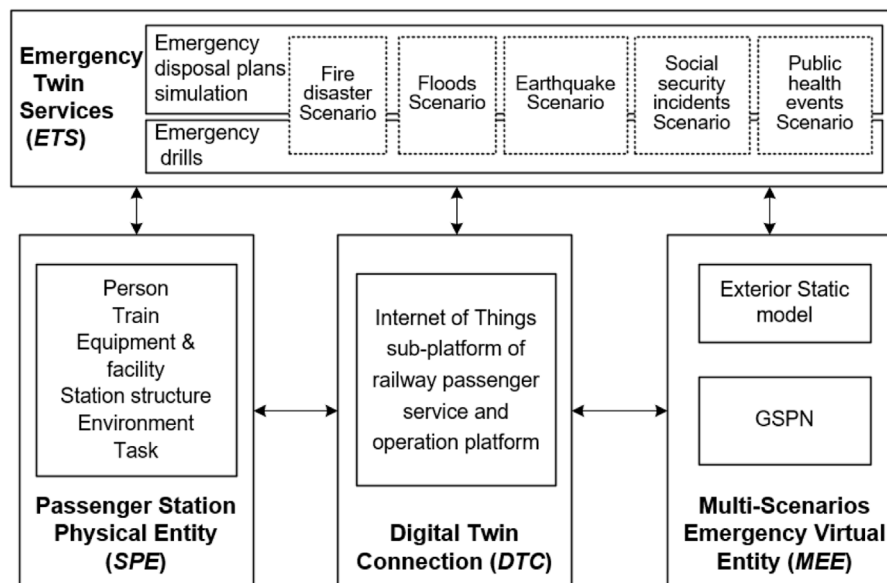
FIGURE 4
Four-dimensional Digital Twin model of Emergency Disposal for passenger station (ED4D).

corresponds to P_7, P_8, P_9 and P_{10}, M_{10} corresponds to P_9, P_{10}, P_{11} and P_{12}.

By utilizing Markov to calculate the average time on each state M_i of the GSPN, the determination of the duration of stay at different states is enabled [49]. Specifically, for the evacuation of passengers in group P_8 and P_9 to P_{13}, the duration BIT is closely linked to the number of passengers present, which poses a high risk of stagnation in state transition. P_{13} can lead to deadlock states in a Petri net, where the system is unable to progress and emergency procedures cannot be executed properly. By analyzing bottleneck P_{13} and promptly adjusting or supplementing them, we can optimize the entire emergency process and ensure smooth emergency handling.

4 Digital twin-based model for multi-scenario emergency

Utilizing the innovative digital twin technology as outlined in [21], we have developed a groundbreaking model consisting of four key components that effectively address emergency scenarios that may arise within passenger stations. This comprehensive model takes into account emergency events, personnel, equipment, resources, and individual actions, with designated personnel implementing a series of emergency response measures in a specific sequence. The 4-dimensional multi-scenario emergency model for passenger stations, known as *ED4D*, is formulated as a set of guidelines that are designed to effectively manage multiple potential emergency situations.

$$ED4D = \{SPE, MEE, DTC, ETS\} \qquad (4)$$

The set *ED4D*, as depicted in Eq. 4, has been established for multi-scenario emergency and disposal at passenger stations. This model consists of four crucial components, namely, the Passenger

Station Physical Entity (*SPE*), Multi-Scenario Emergency Virtual Entity (*MEE*), Digital Twin Connection (*DTC*), and Emergency Twin Service (*ETS*), which are clearly depicted in Figure 4. The following sections provide a detailed explanation of each component. The passenger station physical entity refers to a physical location designed to hold passengers as they board and alight. On the other hand, the multi-scenario emergency virtual entity is a virtual replica connected to its corresponding physical counterpart. The digital twin connection serves as an effective medium for exchanging data between the two realms, while the emergency twin service provides essential services to handle emergencies at the station.

4.1 Passenger station physical entity (*SPE*)

The Passenger Station Physical Entity is comprised of human (*HUM*), train (*TRA*), equipment and facility (*EQU*), station room (*ARC*), and environment (*ENV*), as follows:

$$SPE = \{HUM, TRA, EQU, ARC, ENV\} \qquad (5)$$

The precise details regarding every constituent element have been illustrated in Table 3. Nevertheless, the aid worker, equipment, and facility employed in an emergency situation may vary depending on the type of incident. For additional information of the incidents, please refer to Table1.

4.2 Multi-scenario emergency virtual entity (*MEE*)

In order to create a virtual representation of the passenger station, it is necessary to accurately replicate both the stationary

TABLE 3 Common physical entity details for all scenarios emergency of passenger station.

Class	Details
persons (*HUM*)	Staff, passengers, Aid workers
trains (*TRA*)	High-speed train, General-speed trains
equipment and facilities (*EQU*)	Loudspeaker, platform/Entry/check-in/Guiding screens, self-service ticket checking machine, real-name verification gate, security check instrument, security gate, camera, mobile emergency screen, evacuation indicator light, access control, automatic external defibrillator, help button
station rooms (*ARC*)	Station square, waiting hall, ticket hall, self-service, comprehensive service, Entrance/Exit/Transfer hall
environment (*ENV*)	Temperature, humidity, brightness, harmful gases

and moving attributes of physical objects within the digital realm. The multi-scenario emergency virtual entity comprises a Static model of the exterior, as well as a Dynamic Behavior Model that outlines the emergency response process based on the GSPN framework detailed in Section 3.2.

4.2.1 Exterior static model

To obtain a 3D representation and external image of a physical entity, on-site surveying is necessary to obtain geometry and texture information for trains, equipment, and facilities. One must retrieve the necessary geometric and texture information. In the case of a station structure, construction drawings are utilized for basic geometric information, while on-site photos are utilized for texture information. Personnel are differentiated based on their attire, with staffers further differentiated by gender.

4.2.2 Emergency process dynamic behavior model

In Section 3.2, the GSPN framework is utilized to create a multi-scenario emergency disposal process. The model is implemented in C# using object-oriented programming principles and involves ontology attributes and data related to personnel, trains, equipment, station houses, and environment. The emergency process comprises of different stages such as alarm, start of emergency, disposal, recovery, end, and summary. To simulate passenger arrival parameters, a log-normal distribution is used [50]. Staff are determined by the day's schedule, and train scheduling follows the charting plan for the day. Equipment operation is based on the equipment operation plan, and if an emergency disposal process encounters equipment failure, the Boolean value of the equipment status is changed accordingly.

4.3 Digital twin connection (*DTC*)

The physical entity of the passenger station and the Multi-Scenarios Emergency Virtual Entity both utilize the Internet of Things subsystem of the IRPS for integrated access and management, facilitating connectivity and interaction. In terms of person-to-person connection, staff members use Bluetooth positioning to obtain real-time location information and handheld terminals to send and receive information. The

platform and dispatching system-level interface are utilized to obtain information about train arrivals and departures. Common protocols are used to interactively control electronic equipment such as self-service ticket machines, real-name verification gates, speakers, and various types of screens. Additionally, for system-level interfaces like equipment and trains, we use the HTTP protocol for data acquisition, updating it at predetermined intervals. For real-time train arrival and departure information, the GET method is used, with an approximate cycle of 20 s. For train ticket availability, the POST method is adopted, with a frequency of about once per minute. For passenger and staff information, the POST protocol is utilized, while for equipment, the GET protocol is employed with a 1-min cycle. Fire extinguishers and disinfection sprayers are accessed by Radio Frequency Identification and maintained by staff. Real-time sensors such as smoke sensors and water level meters are used to obtain information about the state of the station environment.

4.4 Emergency twin service (*ETS*)

The digital twin emergence service offers a range of emergency scenario simulation and drill functions for various events. In terms of simulation, the service employs GSPN to automatically calculate the emergency disposal time and effectiveness based on a range of factors including the onset of the emergency, the station's trains, the number of passengers, the real-time location of staff, and the status of emergency resources and equipment. With regards to drills, the platform facilitates the setting of parameters such as the number of participating passengers, staff, and emergency resources to simulate the emergency disposal process. Both service functions provide real-time information on the status, video inspection, and maintenance of inspected equipment, such as fire extinguishers, fire hydrants, sprinklers, mobile emergency screens, and evacuation instructions.

5 A case study for Qinghe station

At Qinghe station, we conducted the validation of digital twin-based solution. The components of the station psychical entities include *HUM* (staff and passengers), *TRA* (high-speed trains), *EQU*, *ARC* (one underground level and three above-ground levels), and *ENV*. Utilizing 3D Max software, we captured on-site real scenes to generate the Exterior Static Model, employing these models to create a multi-scenario virtual entity of Qinghe Station. We utilized Unity3D [7] to develop GSPN processes to create the Emergency Process Dynamic Behavior model, enabling the implementation of all *ETS* functionalities. *DTC* was used to interact with reality and obtain real-time data from the Internet of Things subsystem of IRPS, including the train data, tasks, staff information, and more. The *ETS* can simulate the entire process of emergency disposal and display the number of personnel involved, the nature of resources required for disposal operations, and the duration of the evacuation process. The hardware environment used an Intel(R) Core(TM) i9-10900K CPU@3.7 GHz processor, a NVIDIA GeForce RTX 3080 Ti graphics card with 12 GB memory, 32 GB of DDR4 memory, and the Windows 10 operating system. The final size of this model is 3.8 GB.
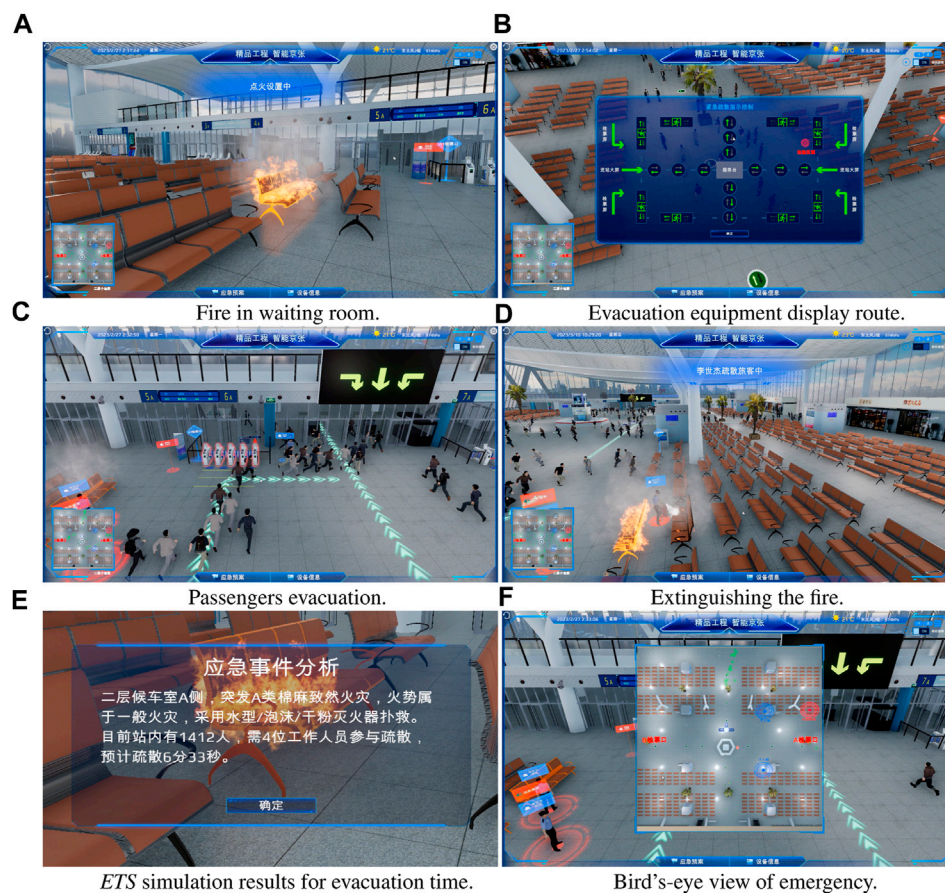
FIGURE 5
Fire scenario. **(A)** Fire in waiting room. **(B)** Evacuation equipment display route. **(C)** Passengers evacuation. **(D)** Extinguishing the fire. **(E)** ETS simulation results for evacuation time. **(F)** Bird's-eye view of emergency.

5.1 Fire

We have developed an extensive plan for a fire emergency, which covers the entire process from its initial outbreak to the conclusion. In the event of a fire, the *ETS* will share information about the burning chair (P_1 in GSPN) as indicated in Figure 5A. The rate of flame combustion may differ based on the material, resulting in varying values for the duration (BT_1). Once the burning surpasses the safety threshold (P_2), the station manager assesses the severity of the situation and activates emergency protocols before any information regarding the emergency is activated (P_3). Next, the staff executes the emergency disposal plan, with some of them seeking help from aid workers, such as firefighters (T_5). The *ETS* then gives information about staff present on the site (P_6), as well as the evacuation equipment executing the emergency disposal (P_7), which provides guidance on the prescribed evacuation route, as shown in Figure 5B. In addition to displaying the staff members responsible for organizing passenger evacuation (T_8), the *ETS* also provides instructions for a group of passengers (T_{13}) to follow and evacuation equipment to use in order to ensure a smooth evacuation process, as illustrated in Figure 5C. Additionally, during the disposal process, the *ETS* displays the staff responsible for extinguishing the fire (T_{14}) and those involved in restoring the scene after the fire has been

extinguished, as depicted in Figure 5D. Finally, the *ETS* delivers the concluding information (P_{16}), and a report on the emergency disposal is produced to document the resolution of the incident.

By simulating emergency disposal plans in the event of a fire scenario, *ETS* can improve the disposal process and achieve desired outcomes. These outcomes are illustrated in Figure 5E, which displays the analysis and results of the simulation of fire disaster emergency disposal plans. The station has 1,412 individuals, and four staff members are responsible for guiding passenger evacuation (T_8). The evacuation takes 6 min and 33 s to complete. Conducting emergency drills for *ETS* in fire scenarios allows staff to practice responding to simulated fire outbreaks in various locations, thereby enhancing their preparedness. It also provides an overview of the entire emergency disposal process, including resource location, disaster location, and passenger evacuation, among other elements, as shown in Figure 5F. The red circle marks the location of the accident, while the blue circle indicates the position of emergency resources.

5.2 Flood

For the scenario of flood, we set up a overall process covering the water-level rise, report, disposal, and conclusion. Initially, the
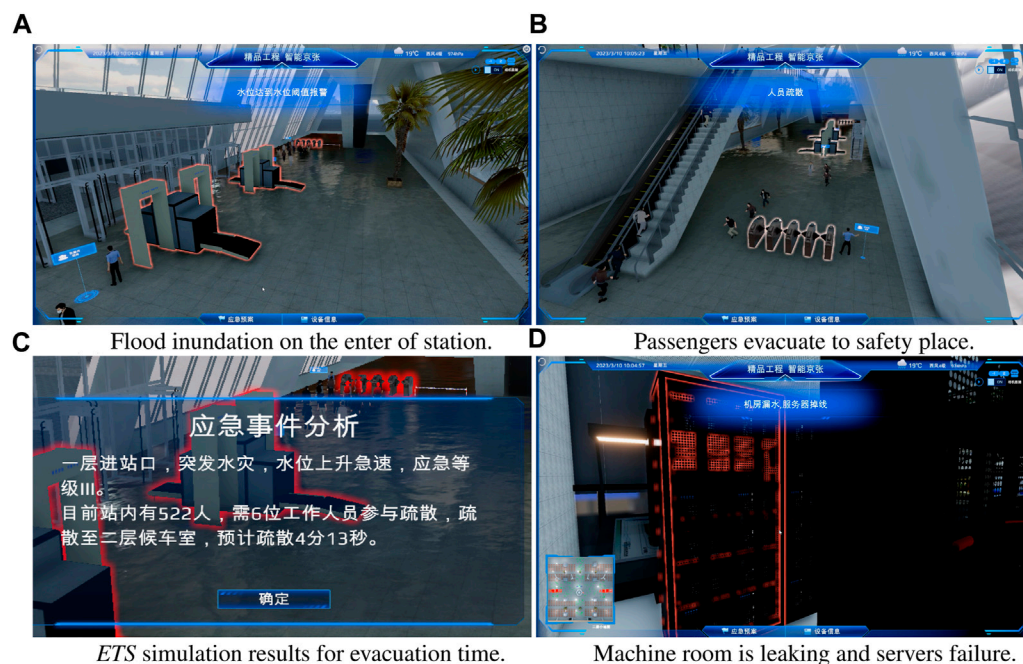
FIGURE 6
Flood scenario. **(A)** Flood inundation on the enter of station. **(B)** Passengers evacuate to safety place. **(C)** ETS simulation results for evacuation time. **(D)** Machine room is leaking and servers failure.

monitoring system provides an overview of the floodwater level entering the interior. As the water level continued to rise (T_1), the floodwater submerged the security check instruments, as depicted in Figure 6A (highlighted in red). The station manager evaluated the severity of the disaster and instructed the implementation of emergency procedures (T_2). At this point, the emergency level was determined to be level 3, and the ETS signaled the initiation of the emergency response (P_3). The emergency tasks were assigned to staff members at each location. These tasks included running to designated locations (P_6) and executing assigned duties (T_8) for some staff members, while equipment displayed emergency information (T_6 and T_{10}), and some staff members directed the evacuation of passengers (P_9).

The passengers adhered to the instructions given by the staff and utilized the evacuation equipment in order to carry out an organized evacuation process (T_{13}), as illustrated in Figure 6B. The staff then proceeded to open the pump (P_{14}) and restore the scene once the pumping was completed at (P_{15}). A report was compiled to document the conclusion of the incident, which is known as the emergency disposal report (P_{16}). Additionally, the emergency disposal plan simulation outlines the plans execution process and results. The flood simulation results, presented in Figure 6C, indicate that the disposal process involved the utilization of pumping pumps, the participation of 6 workers, and the evacuation of 522 individuals from the station. All these actions were successfully executed within a time frame of 4 min and 13 s. Furthermore, conducting emergency drills in flood scenario allows for setting the scale of water and simulating damage to various equipment, such as machine room leakage, as demonstrated in Figure 6D. This facilitates the smooth execution of the flood emergency drill.

5.3 Earthquake

For the scenario of earthquake, passengers experienced a sense of panic upon receiving an earthquake warning (P_1), as illustrated in Figure 7A. The staff on duty immediately responded to the warning and notified the station manager, who evaluated the situation and initiated the emergency protocol (T_3). The assigned staff members were responsible for implementing emergency procedures, including contacting the local earthquake rescue department (T_5), moving quickly to designated locations (T_6), and disseminating information about the emergency train stop (P_7), as demonstrated in Figure 7B. The staff successfully coordinated the evacuation of passengers (P_9), guiding them in an orderly manner using evacuation equipment and staff assistance (T_{13}), as shown in Figure 7C. The entire earthquake scenario was simulated by the solution, which provided valuable insights into the implementation process and the outcomes of the plans. The results of the earthquake simulation, as presented in Figure 7D, indicated that there were 1,478 individuals present in the station during the evacuation, involving the participation of 12 workers and lasting for a duration of 9 min and 46 s.

5.4 Social security incident

The social security situation is employed to tackle the disturbance created by individuals who present a threat to the station. An undisciplined person set fire to their carry-on luggage (T_1), as illustrated in Figure 8A. The responsible staff detected it and immediately notified the station manager to commence emergency disposal. The manager evaluated and initiated the emergency response
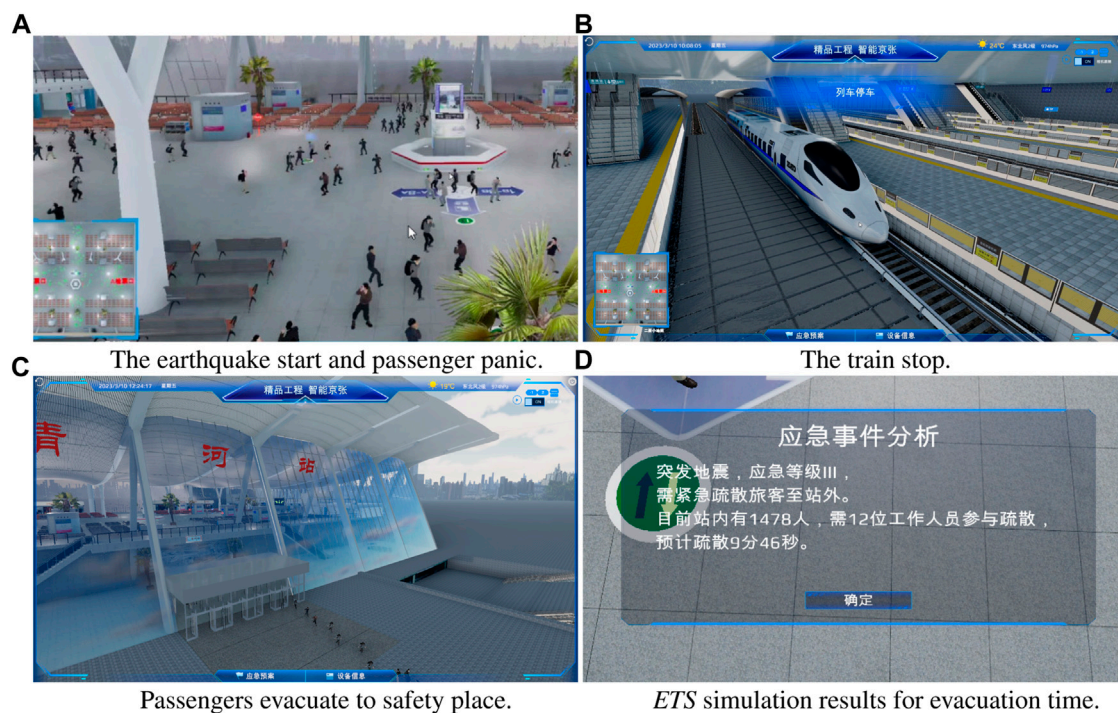
FIGURE 7
Earthquake scenario. **(A)** The earthquake start and passenger panic. **(B)** The train stop. **(C)** Passengers evacuate to safety place. **(D)** ETS simulation results for evacuation time.

(T_3). Subsequently, the station staff contacted the local public security department (P_5), and the public security personnel quickly arrived at the designated location (T_5), while the station staff equipped with mobile screens arrived at the assigned site (P_6) as depicted in Figure 8B.

Simultaneously, additional personnel obtained fire extinguishers to handle the fire (P_6), while a staff member organized the passengers' evacuation according to prescribed procedures (P_9). Public security personnel apprehended the culprits (T_{12}) and restored order to the scene, as shown in Figure 8C. The passengers ensured an orderly evacuation process by complying with staff instructions and the displayed evacuation equipment routes (T_{13}). Lastly, a report on emergency disposal was compiled to document the conclusion of the incident (P_{16}). The simulation process and results are provided by ETS. According to Figure 8D, there were 1,255 individuals in the station, requiring the involvement of 4 personnel for guidance, with the entire evacuation process taking 4 min and 51 s.
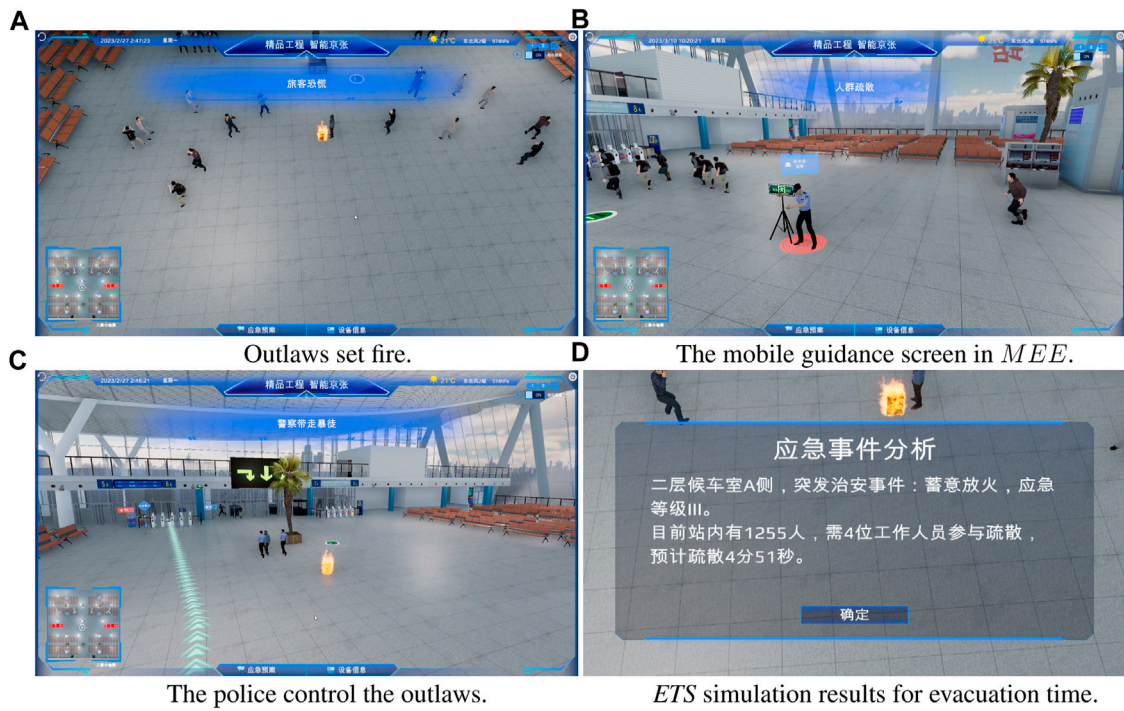
5.5 Public health event

In the event of a public health emergency at a station, the station personnel will receive notification of a passenger carrying a contagious disease. The alert message will appear on the ETS (P_1), prompting the station manager to initiate emergency protocols and release information to staff members (P_3). A staff member will then contact the local epidemic department (T_4), while another staff member locates the infected passenger at the designated location (P_6) as illustrated in Figure 9A, closing the entrance gate to prevent further spread of the disease (P_7) as

illustrated in Figure 9B. The epidemic prevention department will then rescue the passenger (P_8).

To prevent the spread of the disease, individuals who have had no contact with the infected passenger will be screened and evacuated according to staff guidance (T_{13}). The disposal staff will erect an isolation barrier (P_{14}) as illustrated in Figure 9C. Once the situation is fully under control, emergency protocols will be terminated, and an emergency disposal document will be created (P_{16}). The simulation results of public health event are presented in Figure 9D, showing that 933 people were in the station and that four workers were required for the evacuation task, which took 3 min and 55 s.

6 Usability evaluation

In order to validate the efficacy and efficiency of the ED4D, we conducted an assessment from three different perspectives: replication of real-world scenarios, simulation of emergency scenarios, and user-friendliness. The replication of real-world scenarios was utilized to gauge the degree of similarity between the virtual entity's and the physical entity's location, structure, quantity, and information data. The simulation of emergency scenarios was employed to assess the functional accuracy of the emergency process, with a focus on verifying whether the emergency treatment digital twin meet actual operational requirements and whether any critical steps are missing or inconsistent with reality. User-friendliness was measured by evaluating the ease of use and acceptability of the digital twin during practical use, including aspects such as ease of operation and the difficulty of task completion.

FIGURE 8
Social security incident scenario. **(A)** Outlaws set fire. **(B)** The mobile guidance screen in MEE. **(C)** The police control the outlaws. **(D)** ETS simulation results for evacuation time.
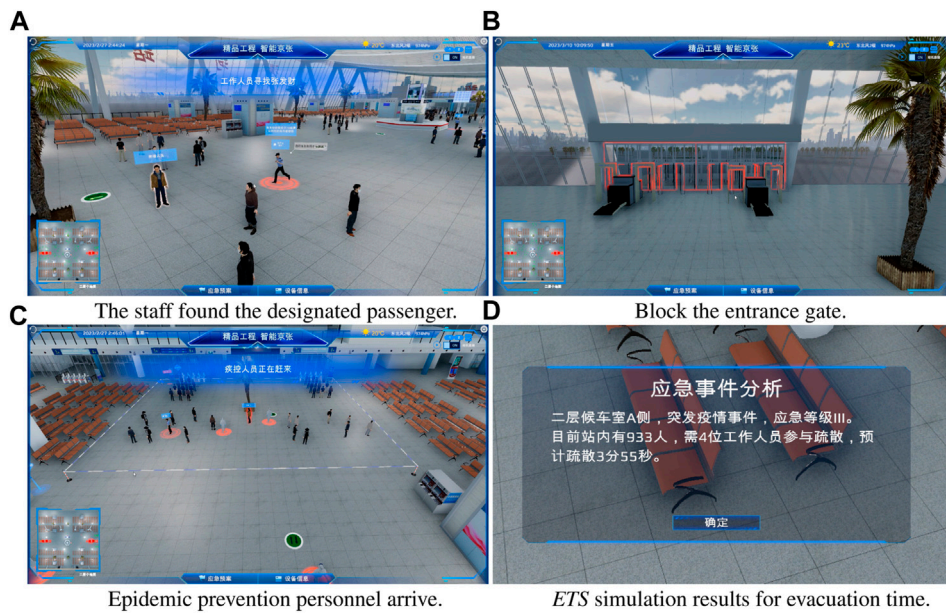
FIGURE 9
Public health event scenario. **(A)** The staff found the designated passenger. **(B)** Block the entrance gate. **(C)** Epidemic prevention personnel arrive. **(D)** ETS simulation results for evacuation time.

6.1 Questionnaire design

The questionnaire was specifically designed to cover the three evaluation aspects. The questionnaire was developed based on the usability metric from user experience framework [44], incorporating the core principles of HEART [45]. The scores were calculated using the SUS [43] based on the search questionnaire. Retaining happiness, engagement, adoption, and task success, the core idea of HEART discarded retention, which was not relevant to the application scenario, as it is intended as a tool in the workplace. After-Scenario Questionnaire [44] was utilized to assess usability, and the results were obtained through questionnaire research and subsequently analyzed.

The questionnaire consists of 12 inquiries, whose specifics are presented in Table 4. The inquiries for reproducing the real-world were designed in terms of station structure, equipment location, and data accuracy. For the simulation of the station emergency scenario, we asked questions about the correctness of the process in five scenarios by using the engagement and task success contents of the core idea of HEART [45]. The being user-friendliness concerns the happiness and adoption of system.

Each inquiry is graded on a scale of "1″" to "5″", wherein "1″" represents strong opposition, "2″" denotes opposition, "3″" represents neutrality, "4″" means agreement, and "5" signifies strong agreement. Questions 1 through 10 are intended to measure positive attitudes, while questions 11 and 12 are for negative attitudes. The SUS score (Brooke, 2013) is determined using Eq. 6.

$$
\begin{cases}
P_s = \sum (S_i - 1) & i = \{Q_1, Q_2, \ldots, Q_{10}\} \\
N_s = \sum (5 - S_i) & i = \{Q_{11}, Q_{12}\} \\
S = \dfrac{P_s + N_s}{c \cdot 12} \times 100
\end{cases}
\tag{6}
$$

Where P_s represents the cumulative sum of positive questions by an individual, N_s represents the cumulative sum of negative; S represent an individual's score, 12 represents the total number of questions, c signify a correction factor expressed as a percentage. The scores of each participant are tallied, with the positive question score being the original score minus 1. Meanwhile, the negative question score is obtained by subtracting the original score from 5. The scores for all 12 questions are added up and converted to a percentage scale. For the purpose of our analysis, we shall designate c as 4.

6.2 Experimental evaluations

In our evaluation, a group of 9 individuals participated, among which 6 had previous experience in passenger transportation, while 2 held managerial experience. Notably, 7 of them, accounting for 77.7%, possessed expertise in emergency disposal. The average age of the participants was calculated to be 34.22 years, with an average career length of 10.33 years. The evaluator conducted the trial through an online platform, utilizing a hardware configuration that consisted of a NVIDIA GeForce RTX 3080Ti graphics card.

In Figure 10, one can observe the distribution of scores for each inquiry, where the color red corresponds to a score of "1″", yellow of

"2″", blue of "3″", green of "4″", and purple of "5". For the first question, six individuals, accounting for 66.7%, provided a raw score of 5. For inquiries two to seven, eight individuals gave a raw score of 4 or greater. With respect to inquiries 8 and 10, seven individuals provided a raw score of 4 or greater. As for inquiry 9, all individuals provided a score of 4 or greater. For inquiry 11, which follows a "the smaller, the better" format, four individuals selected a score of 1. Concerning inquiry 12, five individuals selected a score of 2 or less. In regards to inquiries 4, 5, and 7, the present disposal process aligns with our simulations, underscoring the effectiveness of the ED4D model that has been developed. The short error bars illustrated in the graph suggest the data's reliability.

The data in Table 5 presents the mean and standard deviation for each question. The assessment of inquiry 1, 2, and 3 pertains to the precision of simulating real-world scenarios. The mean scores for each inquiry are 4.56, 4.33, and 4.22, respectively. Their aggregate mean score is 4.37, with a standard deviation of 0.01. The examination results validate that the exterior static model of MEE of ED4D agrees well with SPE.

The inquiries 4, 5, 6, 7, and 8 serve to assess the accuracy of the simulation of emergency scenarios. The assessment reveals an overall mean score of 3.91, with a standard deviation of 0.11. More specifically, the mean scores for each individual inquiry are 4.22, 4.11, 3.33, 4.00, and 3.89. The results of the evaluation demonstrate that scenarios related to fire disaster, flood, and social security incident accurately represent reality with a high degree of precision. With regards to inquiry 6, which pertains to the disposal process for earthquake emergency, users contend that the magnitude of the earthquake should factor into the process, with earthquake below level 3 not requiring consideration. The existing process aligns with the disposal process for earthquake between levels 3 and 6, but is not applicable for earthquake of level 8 or higher. Lastly, in relation to inquiry 8, the existing process for the disposal of public health event scenario is consistent with the prescribed disposal process for the period spanning 2020 to December 2022. However, it is no longer applicable to the disposal process for the new crown epidemic, as policy adjustments were made in 2023.

The inquiries 9 and 10 are utilized to assess the level of contentment. The overall average score obtained stands at 4.11, with a standard deviation of 0.12. The average rating for each question is established at 4.22 and 4.00 respectively. Inquiries 11 and 12 are employed to assess the level of acceptance. The overall average score obtained is 2.11 (note that a lower score indicates better performance), with a standard deviation of 0. The average rating for each question is established at 1.89 and 2.33 respectively. The evaluation results clearly indicate that the functioning of ETS is uncomplicated and user-friendly.

The distribution chart in Figure 11 illustrates the mean scores and number of survey participants in each age group for SUS scores. The evaluation revealed that the 21–30 age group obtained an average score of 77.08, while the 31–40 age group achieved the highest mean score of 82.29. In contrast, the 41–50 age group scored 68.75, and the 51–60 age group scored 58.33. The error bar is relatively short. Furthermore, the nine evaluators who participated in the survey received a mean score of 76.38 points, surpassing the minimum score of 74.1 points, which earned the system a rating of acceptable and the evaluators a grade of good [51,52].

TABLE 4 Questions.

| Questions	Content	Class	HEART	Dimensions
Q1	The exterior Static model of Virtual Entity is consistent with the actual of Passenger Station physical entity building structure	station structure	-	Reproducing the real-world
Q2	The location of the equipment in the scene of Virtual Entity is consistent with the actual of Passenger Station physical entity	equipment location	-	Reproducing the real-world
Q3	The collected data is consistent with the actual of Passenger Station physical entity	data accuracy	-	Reproducing the real-world
Q4	With the *ED4D* model for passenger station, the business process is consistent with the disposal situation of fire disaster, and the function is correct	fire disaster	Task Success and Engagement	Simulating the station emergency scenario
Q5	With the *ED4D* model for passenger station, the business process is consistent with the disposal situation of flood natural disaster, and the function is correct	flood	Task Success and Engagement	Simulating the station emergency scenario
Q6	With the *ED4D* model for passenger station, the business process conforms to the disposal situation of earthquake disaster, and the function is correct	earthquake	Task Success and Engagement	Simulating the station emergency scenario
Q7	With the *ED4D* model for passenger station, the business process is in line with the disposal of social security and is functionally correct	Social security incident	Task Success and Engagement	Simulating the station emergency scenario
Q8	With the *ED4D* model of emergency disposal for passenger station, the business process conforms to the disposal of public health infectious disease, and the function is correct	Public health event	Task Success and Engagement	Simulating the station emergency scenario
Q9	This system is easy to use	-	Happiness	Being user-friendliness
Q10	This system is better integrated in terms of functionality	-	Happiness	Being user-friendliness
Q11	This system takes a lot of time to complete its tasks	-	Adoption	Being user-friendliness
Q12	This system requires additional knowledge to use	-	Adoption	Being user-friendliness
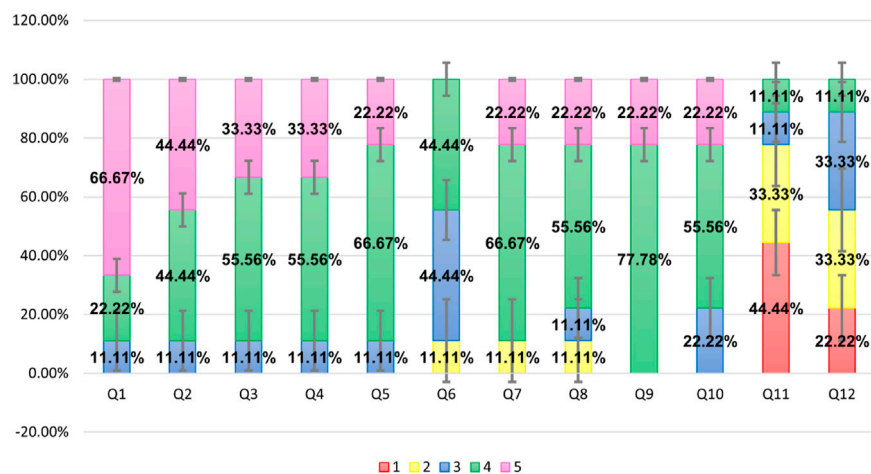
FIGURE 10
Stacked graph of percentage scores for each question.

TABLE 5 Mean and standard deviation.

	Q1 ↑	Q2 ↑	Q3 ↑	Q4 ↑	Q5 ↑	Q6 ↑	Q7 ↑	Q8 ↑	Q9 ↑	Q10 ↑	Q11 ↓	Q12 ↓
Mean	4.56	4.33	4.22	4.22	4.11	3.33	4.00	3.89	4.22	4.00	1.89	2.33
Standard Deviation	0.66	0.66	0.64	0.64	0.60	0.81	0.83	0.89	0.46	0.70	0.98	0.98
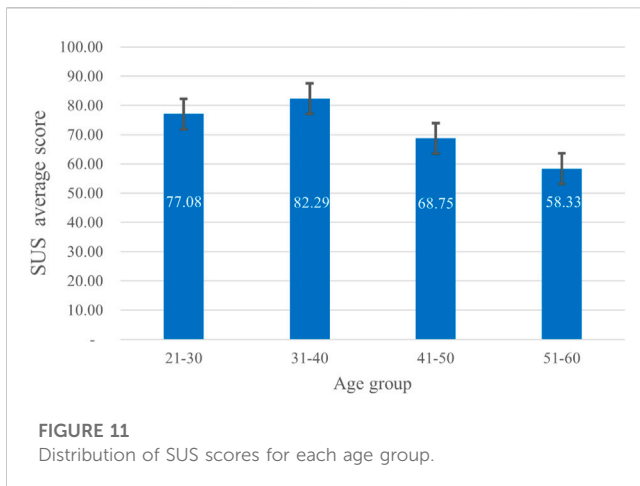
FIGURE 11
Distribution of SUS scores for each age group.

7 Conclusion

To facilitate the training of station personnel in emergency protocols, this research paper has implemented a digital-twin-based approach to create an *ED4D* model for emergency simulation. The model entails the extraction of various emergency scenarios, which are then digitized using GSPN. This process replicates the actual conditions of the physical world within a virtual environment and facilitates the exchange of information between the two spaces. The successful application of this model in constructing multiple emergency scenarios at Qinghe Station, including simulations of fire, natural disasters such as flood and earthquake, social security incident, and public health event, has enabled the effective simulation of emergency procedures and the execution of emergency drills with greater efficiency. In comparison to tabletop exercises and live drills, this solution offers an immersive experience while conserving resources, making it easily adaptable to various potential hazards.

Furthermore, we have evaluated the application in three key aspects: the replication of the real world, the simulation of the station emergency process, and user-friendliness. Based on the System Usability Scale (SUS) evaluation, the overall conclusion was graded as *good*, indicating that the application is suitable for emergency response in passenger stations. This model allows for the validation of emergency plans and the identification of vulnerabilities in the response process. It assists personnel in adjusting resource allocation and strengthening weak areas, thereby enhancing the efficiency of emergency response strategies. Additionally, it establishes a solid foundation for the digitalization and informatization of the emergency response modeling process. Furthermore, the *ED4D* model enables immersive drills for various disaster events, thereby improving the emergency response skills of staff members.

The developed *ED4D* model demonstrates significant applicability as it can encompass the entire process of various disasters, including pre-event preparation, mid-event management, and post-event recovery. Moreover, the design of the GSPN model allows for easy adaptation to other railway passenger stations, highlighting its wide-ranging applicability. Exterior Static models, such as personnel, trains, and equipment, can also be adjusted and

reused in different scenarios, further enhancing the practical value and potential for widespread adoption of this research. It is worth noting that the system developed in this study is currently only operational on computers. Moving forward, our plan is to utilize mixed reality devices to observe staff behavior, thereby achieving an emergency twin service that accurately reflects the composition of real multi-class passengers.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

XW: Methodology, Software, Validation, Writing–original draft, Writing–review and editing. WB: Software, Validation, Writing–original draft, Writing–review and editing. YS: Writing–original draft, Writing–review and editing. GY: Software, Validation, Writing–original draft. CL: Software, Validation, Writing–original draft. XL: Software, Validation, Writing–original draft. KP: Software, Writing–original draft. JL: Validation, Writing–original draft.

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Conflict of interest

Authors WB, GY, CL, XL, KP, and JL were employed by Institute of Computing Technology, China Academy of Railway Sciences Corporation Limited.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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