Evacuation Study with On-site Response Action Manual Using PRISM

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1. Introduction

In the event of a nuclear power plant accident, rapid and effective evacuation planning is a crucial for minimizing radiation exposure. Evacuation and protective actions—including evacuation, sheltering, and relocation—are essential components of emergency response strategies, significantly reducing the consequences of nuclear incidents. These actions are also critical in various other societal disasters, such as fires and earthquakes. [1]

Although emergency preparedness plans include evacuation training as part of nuclear disaster response actions, large-scale real-world evacuation drills for residents are often impractical due to logistical constraints. The challenges associated with organizing mass evacuations necessitate alternative approaches, such as computational simulations, to evaluate and improve evacuation strategies effectively.

To address these challenges, this study employs PRISM (Platform for Radiological Emergency Integrated Simulation Model), an established ABM(Agent-Based Model), to simulate evacuation scenarios during nuclear power plant emergencies, with the aim of deriving strategies to optimize evacuation time. PRISM utilizes ABM techniques to simulate evacuation processes by analyzing the interactions between individual agents and their environments. One of the key advantages of ABM is its ability to represent complex, emergent evacuation patterns that cannot be easily captured through conventional mathematical models. Specifically, PRISM can analyze variations in evacuation times influenced by agent panic levels and intervention by emergency response personnel. Additionally, PRISM is built on the NetLogo platform, allowing it to simulate various evacuation routes and movement speeds based on agent interactions.[2]

This study aims to enhance the realism of nuclear emergency evacuation simulations through collaboration with Busan City. Specifically, the research focuses on developing evacuation scenarios for residents within a 5km radius of the Kori Nuclear Power Plant, categorized as the Precautionary Action Zone (PAZ). By incorporating real-world emergency response guidelines and conducting numerous randomized simulations using PRISM, this study performs uncertainty and sensitivity analyses of evacuation routes to identify optimal evacuation strategies.

2. Review of Field Response Action Manual

2.1. Legal Basis and Scope of Application

Busan City established the ‘On-site Response Action Manual for nuclear safety(radiological release)’ to protect residents in the event of a nuclear power plant accident. The manual draws on authoritative legal frameworks including the ‘Framework Act on the Management of Disasters and Safety,’ the ‘Act on Physical Protection and Radiological Emergency of Nuclear Facilities,’ and the ‘National Crisis Management Basic Guidelines**.’** It mandates coordinated responses led by the Busan City Radiological Emergency Response Headquarters. This effort involves close cooperation with district-level emergency response centers and various relevant organizations. These include police departments, fire departments, maritime police, medical institutions, educational offices, and railway authorities.[3]

2.2. Response Procedures for Nuclear Emergencies

The manual categorizes nuclear emergency severity into three levels—Facility Emergency, Site Area Emergency, and General Emergency—with clearly defined response actions for each level.

Facility Emergency (Initial Warning Level) involves enhanced radiation monitoring, dissemination of alerts to key organizations, and preparation for possible emergency response activities, given the low probability of radioactive releases at this stage.

Site Area Emergency (Precautionary Level) is initiated when the likelihood of radioactive release increases significantly. This level entails radiological exposure assessments and the preparation of protective actions, such as shelter-in-place and evacuation arrangements. The Radiological Emergency Response Headquarters is activated to manage traffic controls, establish temporary shelters, and prepare the distribution of thyroid protective agents.

General Emergency (Severe Emergency Level) is declared when the risk of radioactive material release into the environment becomes imminent or actual. Immediate evacuation of residents within the PAZ is executed, while residents within the Urgent Protective Action Planning Zone (UPZ, 5 to 30 km radius) are directed to initially shelter in place and then undergo staged evacuation. In this level, emergency actions include operation of emergency shelters, medical support services, disaster information broadcasts (Disaster Information Transfer System, DITS), and emergency text messaging (Cell Broadcasting Service, CBS).[3]

2.3. Resident Evacuation Procedures and Assembly Point Managements

Resident evacuation procedues are structured around designated assembly points such as community centers, bus stops, school playgrounds, and apartment parking areas. Residents who use group transportation are instructed to gather at these first-staged assembly points. From there, residents are transported via provided transportation modes—buses, trains, and vessels—to predetermined temporary housing facilities. Specifically, residents transfer by bus from initial gathering points to secondary assembly areas (such as Jwacheon Station and Ilgwang Station), subsequently boarding trains to designated evacuation shelters including Gangseo Sports Park, Daejeo Elementary School, and Daesa Elementary School. Upon arrival at these shelters, evacuees undergo radiation contamination screening, receive thyroid protective agents, and are provided with necessary relief supplies. This structured approach ensures efficient management of large populations during evacuation, reduces potential traffic congestion, and facilitates rapid, orderly emergency response actions.[3]

2.4. Incorporation of the Action Manual into PRISM

The Busan City evacuation manual is systematically structured and regularly improved based on actual evacuation drills. This study seeks to use simulation as a proposed method to complement the outcomes of these practical evacuation drills. Simulations offer the advantage of representing variables such as traffic congestion and changes in transportation modes, thereby potentially contributing to improved disaster management capabilities.

Agents in PRISM are modeled to first move individually from their residences to the initial assembly points (community centers, bus stops, school playgrounds, apartment parking areas, etc.), and subsequently utilize collective transportation methods (buses) toward highway exit points leading to designated evacuation shelters. Consistent with the Busan City Manual, the evacuation initiation time in PRISM simulations is set immediately upon the declaration of a General Emergency—reflecting a scenario in which radioactive release is highly probable. The number of agents was set to 10,000, based on the PAZ population statistics of Gijang, which identifies approximately 8,900 residents within the PAZ area. Additionally, an estimated 1,000 tourists were included to account for the presence of visitors in the region, bringing the total simulated population to 10,000. This approach ensures that the simulation reflects both permanent residents and transient populations who may be present at the time of an evacuation.

Total evacuation times calculated by PRISM thus encompass both the duration required for residents to reach assembly points and the subsequent transportation time to evacuation facilities.

3. Case Studies

The simulation case study was conducted based on the manual, and the results of each scenario setup are shown in Table 1. The evacuation involved 10,000 agents, and each scenario was simulated 50 times to obtain the average evacuation time.

Table I: Outcomes of the Evacuation Scenario Setup

	Average Time (s)	Standard Deviation
Case 1	570.04	1.324
Case 2	3006.8	12.01
Case 3	3160.5	18.81
Case 4	1408.4	33.391

1) Case 1: 100% vehicles (evacuation using self-cars)

This scenario assumes that all residents evacuate individually using their own vehicles. It reflects the manual's directive to prioritize the use of vehicles and the likelihood that most residents will use their own vehicles in the event of an incident. The simulation model accounted for potential traffic congestion along major evacuation routes, ensuring a realistic assessment of vehicle-based evacuation efficiency.

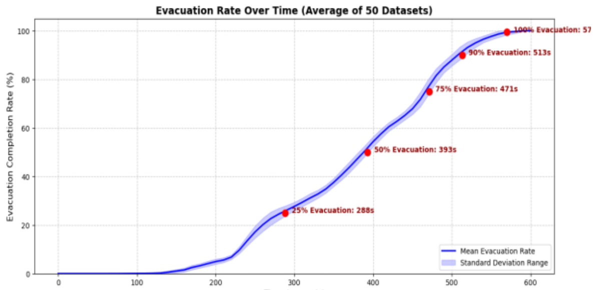

Fig 1. Outcome of Case 1

Referring to Table II, in this scenario analysis, the evacuation time was the shortest, and the standard deviation was low (570.04 s, SD = 1.324), indicating stable movement. The efficient evacuation time can be attributed to the fact that when residents use vehicles, they can move quickly and directly proceed to the shelter without passing through an assembly point. The evacuation progress over time is further illustrated in Figure 1, which shows the evacuation rate curve based on 50 simulation datasets. The curve depicts how quickly residents were able to complete their evacuation. The smooth curve suggests a consistent evacuation flow with minimal disruptions, as expected with vehicle use. In a real-world situation, unexpected road incidents can impact evacuation time. Moreover, since not all residents may have access to vehicles, the actual evacuation time could be longer.

2) Case 2: 50% vehicles and 50% group transportation (buses)

This scenario assumes that 50% of the residents use vehicles for evacuation, while the remaining 50% walk to designated assembly points to take buses. This setup considers that not all residents own vehicles and is aimed at alleviating traffic congestion through a dispersed evacuation strategy. Through this scenario, the impact of a mixed strategy on evacuation time can be analyzed, allowing for the optimization of the distribution ratio between and group transportation. As shown in Table 1, this scenario resulted in a significantly longer evacuation time compared to Case 1, with a mean time of 3006.8 seconds and a SD 12.01.

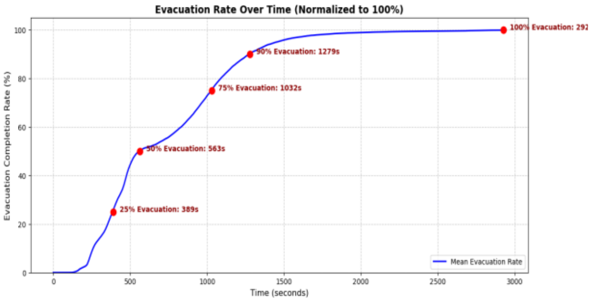

Fig 2. Outcome of Case 2

The evacuation progress over time, illustrated in Figure 2, shows that the evacuation rate initially increased quickly but slowed considerably after reaching 50% completion. The graph confirms that while early evacuation proceeded efficiently, delays in bus availability and capacity constraints significantly extended total evacuation time.

3) Case 3: 100% group transportation (buses)

This scenario assumes that all residents walk to their designated assembly points and then board buses to proceed to the final shelter. According to the Busan evacuation manual, residents without vehicles are instructed to walk to designated assembly points in their respective areas. Consequently, this scenario is designed to evaluate the evacuation time when all residents rely on group transportation rather than individual vehicles. This strategy could minimize traffic congestion and enable a rapid, systematic evacuation. However, the potential impact of the walking component on vulnerable groups—such as the elderly and individuals with disabilities—must be taken into account. Additionally, the effectiveness of group transportation in reducing overall evacuation time can be further examined.

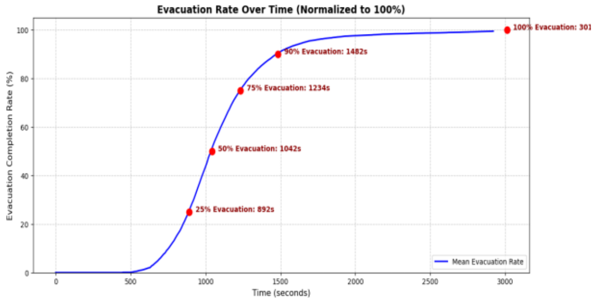

Fig 3. Outcome of Case 3

As shown in Table 1, this scenario resulted in the longest evacuation time, with a mean time of 3160.5 seconds and a standard deviation of 18.81. The extended evacuation duration is primarily due to mass movement toward assembly points, causing congestion and delays in transport boarding. The evacuation progress over time, illustrated in Figure 3, confirms that while early evacuation progressed similarly to Case 2, the final phases took significantly longer due to bus capacity limitations. Additionally, when a large number of people move simultaneously, there is a potential for further delays.

4) Case 4: residents within 500 m walk, while those beyond 500 m use vehicles.

This scenario assumes that residents living within 500 meters will evacuate on foot, while the remaining residents will use vehicles. This reflects the Busan manual's recommendation that residents who can walk should do so to reach the shelter, as it is feasible for those living within a certain distance. Designating specific areas as pedestrian evacuation zones could be an effective strategy to prevent traffic congestion and facilitate rapid evacuation.

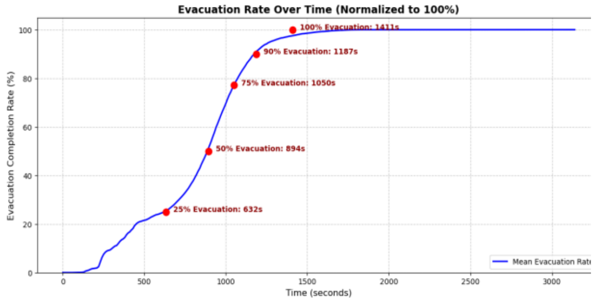

Fig 4. Outcome of Case 4

The evacuation progress over time, illustrated in Figure 4, confirms that early evacuation progressed smoothly, but variations in pedestrian and vehicle movement caused inconsistencies in the final phases. This scenario resulted in a longer evacuation time compared to Case 2 (50% vehicles, 50% group transportation) and a shorter time compared to Case 3 (100% group transportation).

5. Conclusion

This study evaluated four evacuation scenarios based on the Busan evacuation manual using a simulation model with 10,000 agents. The simulation results provided insights into how different evacuation strategies influence total evacuation time, traffic congestion, and efficiency. By analyzing cases with varying transportation methods, the study highlights key factors affecting evacuation performance and potential areas for improvement in emergency planning.

The findings confirm that Case 1 (100% vehicles) resulted in the shortest evacuation time (570.04s), demonstrating that direct travel to shelters without assembly points minimizes delays. However, since not all residents own vehicles, complete reliance on private transportation is not a feasible strategy for large-scale evacuations. Additionally, real-world traffic incidents could introduce additional uncertainties, requiring contingency planning for alternative transport options.

Case 2 (50% vehicles, 50% buses) showed a significantly increased evacuation time (3006.8s) due to delays in bus boarding and transport availability. The results suggest that while a mixed approach can distribute traffic more evenly, transport scheduling and capacity allocation must be optimized to prevent excessive waiting times at assembly points.

Case 3 (100% buses) resulted in the longest evacuation time (3160.5s), highlighting the challenges of large-scale pedestrian movement toward assembly points and the constraints of limited bus capacity. The gradual increase in evacuation completion, as observed in the evacuation rate curve, suggests that while a fully structured group transport approach may reduce road congestion, it introduces significant bottlenecks due to boarding delays, limited bus resources, and pedestrian congestion. The study suggests that phased bus departures, increased fleet size, and designated pedestrian flow control could improve evacuation efficiency in this scenario.

Case 4 (500m walking, vehicles for the rest) demonstrated a middle-range evacuation time (1408.4s), outperforming full reliance on buses while mitigating some of the congestion seen in Case 2. The evacuation curve indicates that while early evacuation occurred smoothly, disparities between pedestrian and vehicle speeds created inconsistencies in the final evacuation phase. This suggests that designated pedestrian-only routes and controlled vehicle-pedestrian interaction points may enhance efficiency in such hybrid evacuation strategies.

Future research should explore real-time traffic adaptation models, integrating dynamic road conditions, intersection control strategies, and emergency lane prioritization to further enhance evacuation planning. Additionally, incorporating demographic considerations, such as elderly and mobility-impaired individuals, into the model would provide a more comprehensive assessment of realistic evacuation dynamics. By refining evacuation strategies through continued simulation-based studies, emergency planners can develop more effective protocols to ensure swift and organized evacuations in real-world scenarios.

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