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REVIEW ARTICLE (INVITED ONLY)

Enhancing Radiological Emergency Response Through Agent-Based Model Case 1: Effectiveness of Staged Evacuation

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Abstract

In the event of radiological emergencies, such as nuclear accidents, the speedy but well-ordering evacuation of residents is imperative to ensure their health and safety. Staged evacuation has been studied as a method to reduce evacuation time. However, a method is needed to confirm the effectiveness of staged evacuation and to optimize the strategy. This study evaluates the performance of staged evacuation with more realistic factors which are implementable in a simulation platform. The evacuation simulation was conducted using PRISM (Platform for Radiological Emergency Integrated Simulation Model), developed by Kyung Hee University and utilizing an Agent-Based Model. A city was modeled using GIS data for road networks, buildings, and administrative districts. The population distribution was made non-uniform based on building layout data, and evacuation areas were divided based on administrative districts for demonstrating purpose. The simulation varied the order of evacuation groups and the evacuation start time interval, comparing evacuation times and average speeds to evaluate each strategy. The results reached a few insights: (1) Certain staged evacuation strategies are effective in reducing evacuation times within the PAZ. (2) A staged evacuation strategy that prioritizes areas closest to the nuclear plant resulted in longer evacuation times compared to other evacuation sequences. (3) There is no significant relationship between evacuation time and evacuation speed. In other words, even if the evacuation times of strategies are similar, the evacuation speeds may differ. Since evacuation speed indicates road congestion, a strategy with a slightly longer evacuation time but a faster evacuation speed may be chosen depending on the objective.

Keywords Staged evacuation · Evacuation strategy · Agent-based model · Radiation protection

Introduction

While the probability of a severe accident at a nuclear power plant resulting in the leakage of radioactive materials is exceedingly low, the potential health hazards to residents and the economic consequences of such an accident are substantial. The Fukushima nuclear disaster in 2011, triggered by an unexpected natural disaster, led to the evacuation of more than 70,000 local residents from the vicinity. Research is underway to remediate the land contaminated with radionuclides [1], and decontamination efforts are in progress in the contaminated areas. However, the recovery has not yet been completed [2], and significant costs are being incurred. Despite various challenges encountered during the evacuation process, the early evacuation efforts ensured that there were no reported cases of radiation exposure among the evacuees [3]. As shown by the Fukushima nuclear accident, early but well-organized evacuation in case of a radiation emergency is an important measure to protect the safety of residents.

In South Korea, radiological emergencies are classified into three levels based on their severity and the anticipated degree of damage: a Facility Emergency (as white alert) where impacts are confined within the building, a Site Area Emergency (as blue alert) where impacts are confined to the facility site, and a General Emergency (red alert) where impacts extend beyond the site.

In the event of a red alert, residents within a 5 km radius of the nuclear power plant, located in the Precautionary Action Zone (PAZ), must evacuate immediately to shelters. According to the National Radiological Emergency Preparedness Plan of Korea [4], each local government is required to establish an evacuation plan aiming to evacuate

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residents within the PAZ within 1–2 h. Additionally, those residing within a 30 km radius, in the Urgent Protective Action Planning Zone (UPZ), are directed to either take shelter indoors or evacuate to shelters, depending on the circumstances. Typically, evacuations are initiated prior to any external leakage of radioactive materials. Nonetheless, the outcome of evacuations in actual accident scenarios may not always be positive. To minimize the risk of radiation exposure for evacuees during the evacuation process, swift evacuation is necessary. The reduction in evacuation time decreases the duration of exposure to radiation, allowing evacuees to arrive at shelters more quickly and receive necessary assistance.

Staged evacuation has been proposed as a method to shorten evacuation times. Unlike simultaneous evacuation, where all residents in the impacted area evacuate concurrently, staged evacuation involves the sequential evacuation of residents from different zones according to a predetermined order. Many researchers have conducted studies on staged evacuation. Chen and Zhan [5] examined staged evacuation strategies in three different road network structures with varying population densities. Yang [6] assessed staged evacuation strategies through simulation, combining pedestrian choice models with agent-based pedestrian behavior simulation models. Park and Jae [7] identified the optimal staged evacuation strategy by segmenting evacuation zones based on level 3 probabilistic safety assessment (PSA) outcomes and employing a mathematical approach to compute evacuation and delay times. Zhao [8] introduced a comprehensive risk assessment method to quantify potential risks in nuclear emergency evacuations and proposed partitioned evacuation organizational strategies and cell transmission models to minimize exposure risks based on the assessment outcomes.

Some studies on staged evacuation have conducted evacuation simulations on theoretical road layouts, such as radial or grid patterns. However, urban environments in reality are comprised of a complex network of roads that vary in form and connectivity. It cannot be assumed that results obtained from simulations on theoretical roads would directly translate to actual road networks [5], highlighting the necessity to model real-world road networks in evacuation simulations. Most research in this area has presumed a uniform distribution of populations or has delineated evacuation groups by dividing the evacuation area with hypothetical boundaries, such as a specified kilometer radius from a nuclear facility, to facilitate staged evacuations. However, in reality, population distribution is not uniform, and the division of evacuation areas cannot be neatly segmented in practical scenarios. The division of evacuation areas in reality cannot be neatly accomplished, and issuing evacuation orders based on distance may lead to residents being unsure if they are subject to evacuation, potentially resulting in shadow evacuations [9, 10]. Such factors, not considered in previous research, could significantly change the outcomes when applied in real-world scenarios.

To overcome these limitations, this study incorporates more realistic elements. It utilizes Geographic Information System (GIS) data of an arbitrary city to model the city's road network and buildings, and sets the initial locations of evacuees at buildings to create a more realistic population distribution. Additionally, it divides evacuation areas based on administrative district GIS data of the arbitrary city. The results of the evacuation simulations are analyzed to examine the impact of staged evacuation on evacuation times and speeds, thereby evaluating the effectiveness of each staged evacuation strategy.

Simulation Methodology

Platform for Radiological Emergency Integrated Simulation Model

This study conducted evacuation simulations utilizing the PRISM [11] (Platform for Radiological Emergency Integrated Simulation Model), a platform developed by Kyung Hee University. PRSIM is an evacuation simulation platform using agent-based model [12, 13] (ABM) and is created as an ABM tool, Netlogo [14]. In NetLogo, the simulation environment is fundamentally composed of four types of agents: Turtles, representing observed entities; Patches, indicating environmental changes; Links, for interactions; and Observers, who act as the observers. These components are utilized effectively to model and observe agents, the environment, and their interactions. A notable feature of NetLogo is its capability to support integration with GIS data.

Evacuee Algorithm

This section introduces the pathfinding and traffic models for evacuees within the evacuation simulation. In this paper, the objective focuses on relative comparing each strategy of staged evacuation, thus well-known pathfinding and traffic model algorithms have been incorporated.

Pathfinding Model

Prior to the initiation of the simulation, it is essential for evacuees to undergo a pathfinding process toward their designated destinations. For this purpose, the study implements the A* algorithm, a heuristic technique predominantly used in traffic navigation systems. The A* algorithm employs an evaluation function, as shown in Eq. 1 [15]:

$$f(N) = g(N) + h^*(N) \tag{1}$$

where $f(N)$: the evaluation function for a path, $g(N)$: the distance from the starting node to the current node N, $h^*(N)$: the distance from node N to the destination, and N: the current node.

This heuristic approach facilitates the selection of an optimal path by comparing costs associated with transitioning states or moving to subsequent nodes, with the introduction of $h^*(N)$ serving to reduce unnecessary visits to intermediate nodes.

Traffic Model

Following the completion of pathfinding, a model is required to simulate the movement of evacuees to their destinations. The Cellular Automata model (CA model) was selected for this task. The CA model addresses the limitations of macroscopic traffic simulation models by allowing for detailed microscopic traffic simulations. The model is based on cells, representing the fundamental spaces occupied by vehicles [16], and is characterized by two states: 0 (no vehicle) and 1 (vehicle present). Each cell's vehicle has a velocity attribute, which can range from 0 to a predefined maximum value.

Evacuation Region

In this study, to more realistically demonstrate the impact of staged evacuation on evacuation times and speeds, a hypothetical coastal town in South Korea, referred to as A-eup (town A), was modeled as the evacuation area based on an arbitrary real coastal city. Figure 1 depicts the modeled evacuation area, A-eup. All GIS data used to model A-eup were downloaded from V-world [17], a geographical spatial information platform operated by the Ministry of Land, Infrastructure, and Transport of the Republic of Korea. The GIS data used for roads, buildings, and administrative districts are road centerlines [18], (Continuous Cadastral Map) buildings [19], and legal boundaries (Ri unit) [20], respectively. Thus, while the location of the power plant was arbitrarily assumed, the roads, buildings, and administrative districts are based on real area data downloaded

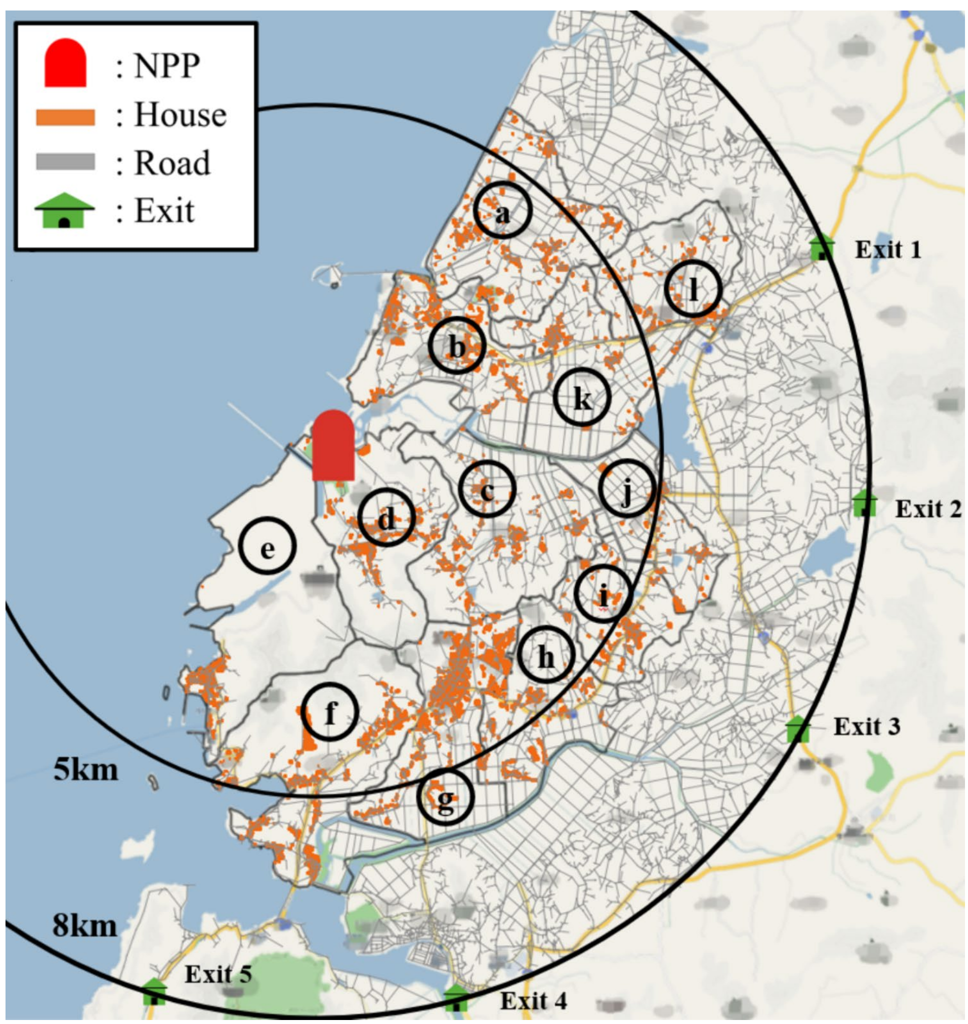

Fig. 1 Map of A-eup, an evacuation area

through open sources. It is assumed that a nuclear power plant is located at the central coastline of A-eup, with nearly all areas of A-eup falling within a 5 km radius of the plant. This means that A-eup is within PAZ of South Korea. Town A is subdivided into 12 administrative districts, known as "Ri(village)". Buildings were modeled only within A-eup, serving as the initial locations of residents at the start of the evacuation. Table 1 lists the number of buildings present in each Ri, with the ratio of the number of buildings in each Ri to the total number of buildings representing the population fraction of each Ri. The population of Town A is assumed to be 10,000, with the population of each Ri calculated by multiplying its population fraction by 10,000. Roads were modeled up to an 8 km radius from the plant, categorized into main roads with a speed limit of 70 km/s and regular roads with a speed limit of 50 km/s. Exits are designated as the points where evacuees exit A-eup during the simulation, with five locations identified where the 8 km radius line intersects with the nearest regular road leading to a main road or outside the 8 km radius. The evacuation time in this study is defined as the time it takes for all evacuees to reach an exit.

Staged Evacuation

As mentioned earlier, staged evacuation is a strategy where evacuation groups divided within the evacuation area evacuate according to a predetermined order. The introduction of staged evacuation serves multiple purposes. Firstly, it allows for the prioritization of evacuating groups based on their level of risk [21]. In such cases, the order of evacuation is determined by the level of risk, and for example, in the case of a radiological emergency, residents closer to the nuclear plant can be evacuated first. Secondly, it aims to reduce evacuation time. Although staged evacuation does not always result in shorter evacuation times compared to simultaneous evacuation, studies [5] have shown that in cities with grid road structures and high population densities, staged evacuation can lead to shorter evacuation times. Thirdly, it seeks to alleviate traffic congestion or increase evacuation speed. If evacuation commences after radioactive materials have already been released, a strategy that minimizes exposure to radiation is necessary. Even if the evacuation time for staged evacuation is not shorter than that for simultaneous evacuation, increasing the evacuation speed can reduce the time evacuees spend on the roads, potentially resulting in less exposure to radioactive materials compared to simultaneous evacuation.

Table 1 The number of buildings, the fraction of population, the population, and the number of vehicles in each Ri

Ri	Number of house	Fraction of population	Population	Number of vehicles
a	1182	0.094	940	470
b	1140	0.09	900	450
c	1225	0.097	970	485
d	1235	0.098	980	490
e	734	0.058	580	29
f	1620	0.128	1280	640
g	2395	0.19	1900	950
h	896	0.071	710	355
i	590	0.047	470	235
j	530	0.042	420	210
k	564	0.045	450	225
l	508	0.04	400	220
Total	12,619	1	10,000	5000

Assumptions for Initial Setup

For the purpose of this study, which focuses solely on analyzing the impact of staged evacuation applied in the PAZ on evacuation times and speeds, it is assumed that no radioactive materials are released during the evacuation process.

It is assumed that evacuees immediately begin evacuating upon the issuance of an evacuation order. While in reality, the preparation or initiation time for evacuation varies among individuals, this study presumes that all evacuees have completed preparations before the evacuation order is issued.

The means of evacuation is limited to personal vehicles. Although there are other modes of transportation such as buses and trains planned by the government in actual scenarios, this study focuses on analyzing the impact of staged evacuation on road traffic, thus considering only personal vehicles as the mode of evacuation. It is assumed that each household consists of two individuals and owns one vehicle. Therefore, with a population of 10,000 in Town A, the number of vehicles participating in the evacuation is 5000.

Evacuation Strategy

Variables for the staged evacuation strategy in this study include the number and method of dividing evacuation groups, evacuation order, intervals between the start times of evacuations, and population size. There are numerous ways to divide the 12 "Ri" into groups. Even dividing them into just two evacuation groups can result in hundreds of scenarios. Therefore, the division was limited to two and three groups, with the "Ri" arranged into each evacuation group in equal numbers based on their proximity to the nuclear plant. Tables 2 indicate the division of "Ri" into evacuation groups, and Figs. 2 and 3 show maps of the 12 "Ri" divided into evacuation groups. All possible evacuation orders were

Table 2 Evacuation groups and Ri corresponding to evacuation groups according to the number of divisions

Number of divisions	Group	Ri
2	I	a, b, c, d, e, g
	II	f, h, i, j, k, l
3	III	b, c, d, e
	IV	a, g, i, k
	V	f, h, j, l

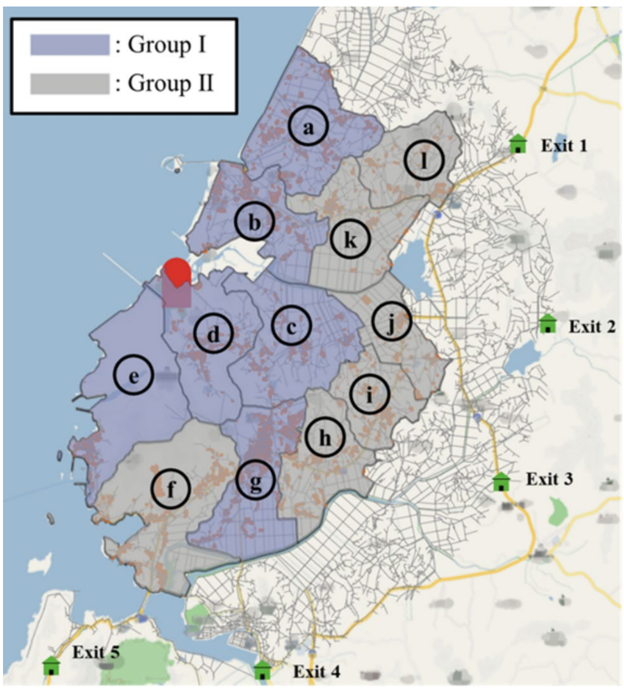

Fig. 2 Map showing evacuation groups (I, II) when the number of divisions is 2

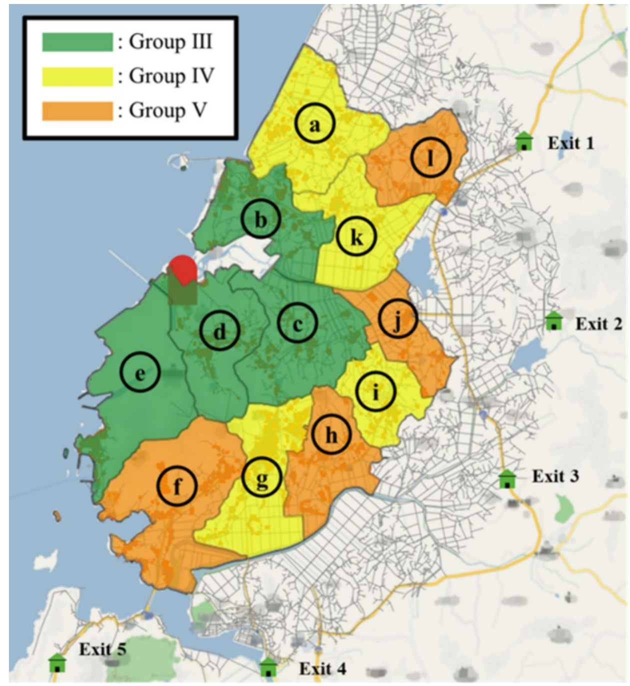

Fig. 3 Map showing evacuation groups (III, IV, V) when the number of divisions is 3

considered. The intervals between the start times of evacuations were arbitrarily set to 5, 10, and 15 min. Each evacuation strategy is summarized in Table 3.

Upon starting the simulation in PRISM, vehicles are randomly generated at buildings within each "Ri" equal to the number of vehicles per "Ri". For example, the 470 vehicles generated in "a-Ri" are randomly placed among 1182 houses in "a-Ri". This serves to further diversify the already non-uniform population distribution among the "Ri". Due to the random generation of evacuees, each evacuation strategy was simulated over ten trials.

Evacuation Time and Speed

The strategies for staged evacuation are evaluated using the evacuation time and speed of each strategy. As mentioned previously, evacuation time is defined as the time it takes until the last evacuee reaches an exit, with PRISM recording the evacuation time immediately upon completion of the evacuation simulation. Since each strategy is simulated ten times, the average evacuation time for strategy i is expressed by

$$\overline{T}_{E,i} = \frac{\sum_{j=1}^{10} T_{E,i,j}}{10} \tag{2}$$

where $\overline{T}_{E,i}$: average evacuation time of strategy I, i: strategy number, j: number of trials, and $T_{E,i,j}$: evacuation time of strategy i at jth trial.

In PRISM, the evacuation speed is recorded every 10 s from the start to the completion of the evacuation simulation as the average speed of evacuation. This average speed refers to the mean velocity of vehicles that are in the process of evacuating, excluding those that have not started evacuating or have already completed evacuation. The average evacuation speed for the jth trial of evacuation strategy i at time t is expressed by

$$\overline{v}_{i,j}(t) = \frac{\sum_{k=1}^{N_e(t)} v_k(t)}{Ne(t)} \tag{3}$$

where $\overline{v}_{i,j}(t)$: evacuation average speed of strategy i at time t and jth trial (km/h), $N_e(t)$: number of evacuating vehicles at time t, $v_k(t)$: speed of kth vehicle at time t (km/h), and k: kth evacuating vehicle.

Table 3 Evacuation strategies based on evacuation start time interval, number of divisions, and evacuation order

Strategy	Interval time	Number of divisions	Sequence
1	–	–	–
2	5 min	2	I–II
3			II–I
4		3	III–IV–V
5			III–V–IV
6			IV–III–V
7			IV–V–III
8			V–III–IV
9			V–IV–III
10	10 min	2	I–II
11			II–I
12		3	III–V–IV
13			III–V–IV
14			IV–III–V
15			IV–V–III
16			V–III–IV
17			V–IV–III
18	15 min	2	I–II
19			II–I
20		3	III–IV–V
21			III–V–IV
22			IV–III–V
23			IV–V–III
24			V–III–IV
25			V–IV–III

Since the number of trials is 10, the average evacuation speed for strategy i at time t is expressed by

$$\overline{v}_i(t) = \frac{\sum_{j=1}^{10} \overline{v}_{i,j}(t)}{10} \tag{4}$$

where $\overline{v}_i(t)$: evacuation average speed of strategy I at time t (km/h).

To compare the speed of each strategy, it is intended to use the average speed. To calculate the average speed, it is necessary to know the function $\overline{v}_i(t)$ of time t, but the only available information is the value of the average evacuation speed ($\overline{v}_i(t)$) recorded every 10 s. Therefore, the Composite Trapezoidal Method is utilized to approximate the average speed. The approximation formula using the Composite Trapezoidal Method is expressed by

$$\overline{V}_i = \frac{\int_0^{\overline{T}_{E,i}} \overline{v}_i(t)dt}{\overline{T}_{E,i}} \approx \frac{\sum_{t=0}^{\frac{\overline{T}_{E,i}}{10}-10\text{s}} \left(\frac{\overline{v}_i(10t)+\overline{v}_i(10t+10\text{s})}{2}\right) \times 10\text{s}}{\overline{T}_{E,i}} \tag{5}$$

$\overline{V}_i$: average speed of strategy i (km/h).

Results and Discussion

Using Eqs. (2) and (5), the evacuation time and average speed for each evacuation strategy were calculated. Figures 4 and 5 illustrate graphs of evacuation time and speed, respectively. When comparing the evacuation time of simultaneous evacuation (Strategy 1) with staged evacuation (Strategies 2–25), the strategies where staged evacuation resulted in shorter evacuation times were Strategies 3, 6, 7, 9, and 11, totaling five strategies. When these five strategies are arranged in order of shortest evacuation time, they follow the sequence of Strategies 3, 9, 11, 6, and 7. Thus, if considering only evacuation time, Strategy 3 emerges as the most suitable evacuation strategy. Conversely, among the 19 staged evacuation strategies that had longer evacuation times than simultaneous evacuation, the five strategies with the longest times, in descending order, are Strategies 24, 25, 16, 23, and 21. Except for Strategy 16, all these strategies involve an evacuation start time interval of 15 min. Strategy 24 is identified as the strategy to avoid when only considering evacuation time.

Comparing the average speeds of simultaneous evacuation (Strategy 1) with staged evacuation (Strategies 2–25) reveals that all staged evacuation strategies had higher average speeds than simultaneous evacuation. This indicates that the introduction of staged evacuation strategies increases the average speed of moving vehicles. Among the 25 evacuation strategies, Strategy 25 had the highest average speed, being approximately twice as fast as Strategy 1.

Figures 6 and 7 illustrate graphs showing the evacuation time and average speed for each evacuation sequence as the interval between the start times of evacuations changes. With the exception of the evacuation sequence I—II (Strategies 10, 18), for all identical evacuation sequences, as the evacuation interval increased by 5 min, so did the evacuation time.

The average speed increased for all evacuation strategies when the interval between the start times of evacuations increased by 5 min within the same evacuation sequence. This indicates that by adjusting the interval between the start times of evacuations within the same evacuation sequence, both evacuation time and average speed can be managed, and the resulting changes are in a trade-off relationship.

Across all evacuation start time intervals, the evacuation sequence II–I (Strategies 3, 11, 19) resulted in the shortest evacuation time. Similarly, for all evacuation start

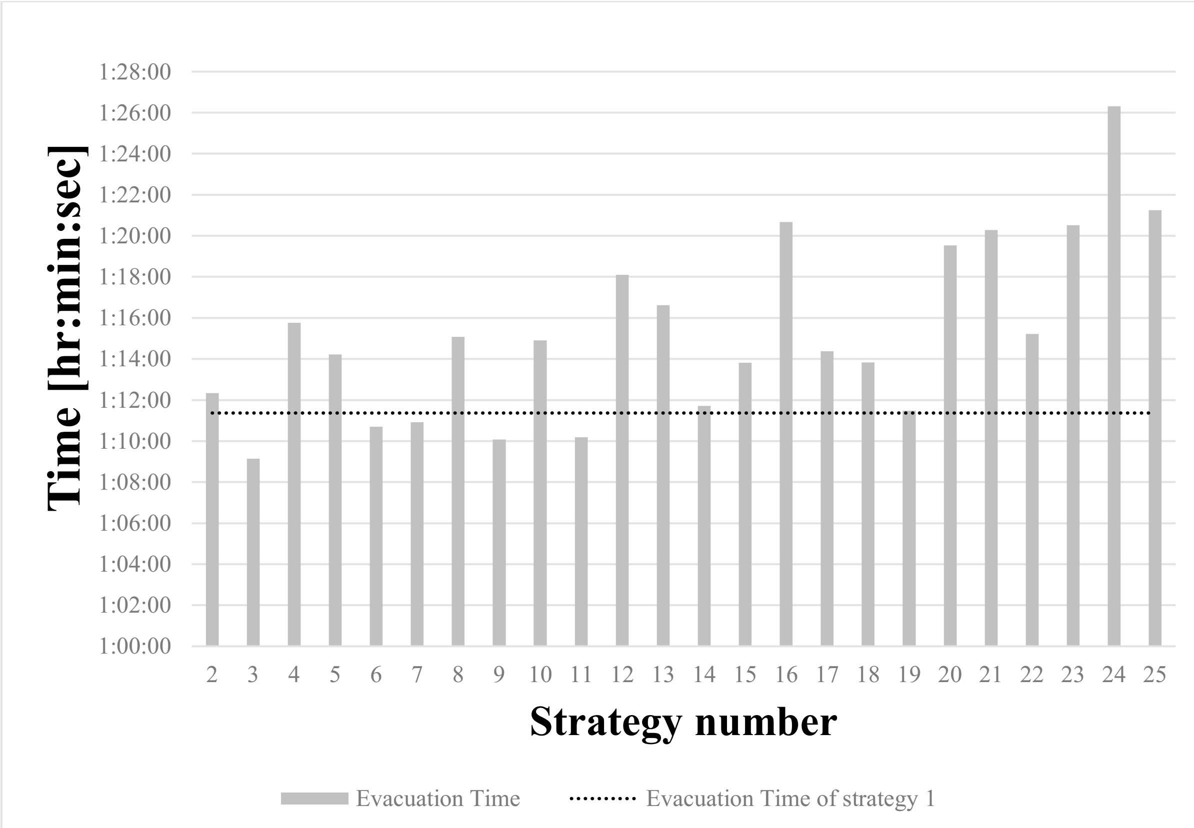

Fig. 4 The evacuation times for each strategy

time intervals, the sequence V–IV–III (Strategies 9, 17, 25) achieved the highest average speed. Therefore, regardless of the evacuation start time interval, the optimal evacuation sequence for minimizing evacuation time is II–I, and for maximizing average speed is V–IV–III.

Conclusions

This study aimed to evaluate staged evacuation incorporating more realistic elements. Evacuation simulations were carried out with varied evacuation orders and intervals between the start times, to calculate each evacuation strategy's time and average speed for analysis and evaluation.

The results reached a few insights: (1) Certain staged evacuation strategies are effective in reducing evacuation times within the PAZ. (2) A staged evacuation strategy that prioritizes areas closest to the nuclear plant resulted in longer evacuation times compared to other evacuation sequences. (3) There is no significant relationship between evacuation time and evacuation speed. In other words, even if the evacuation times of strategies are similar, the evacuation speeds may differ. Since evacuation speed indicates road congestion, a strategy with a slightly longer evacuation time but a higher evacuation speed may be chosen depending on the objective.

This study is significant for evaluating the impact of staged evacuation under more realistic conditions. Future research will focus on the effects of shadow evacuation during radiological emergencies. Shadow evacuation refers to the phenomenon where people voluntarily evacuate from areas not designated for evacuation. This is expected to be a major obstacle to planned evacuations in actual radiological emergency situations. The factors causing shadow evacuation and its impact will be investigated, and the phenomenon will be studied further by incorporating it into PRISM. Another future work will be the evacuation of elderly people during radiological emergencies. Most of the residents living near nuclear power plant sites in South Korea are elderly. By incorporating the elderly population ratio and their characteristics into PRISM, we will analyze the evacuation phenomena. Additionally, we will study methodologies to improve their evacuation.

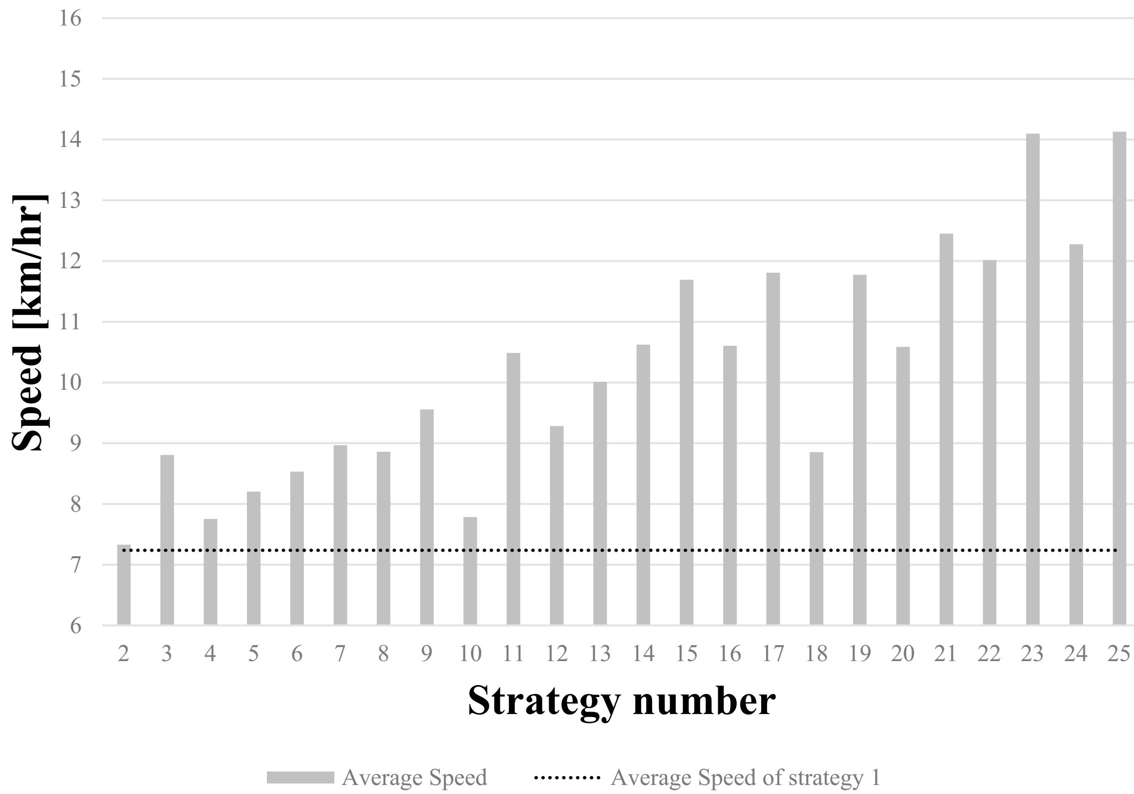

Fig. 5 The average speeds for each strategy

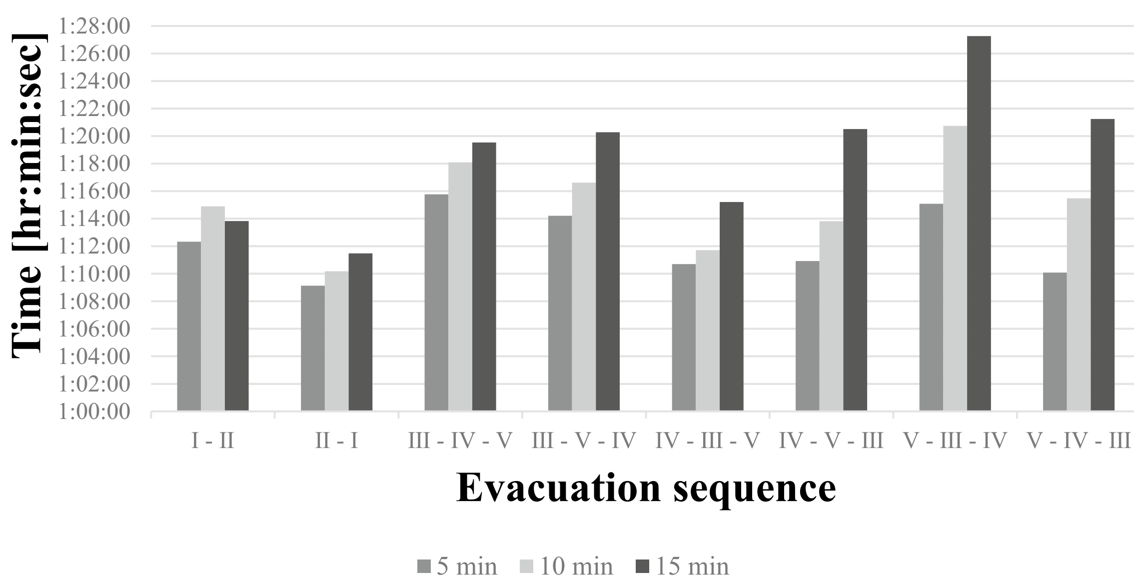

Fig. 6 Evacuation time of each evacuation sequence as the evacuation start time interval increases

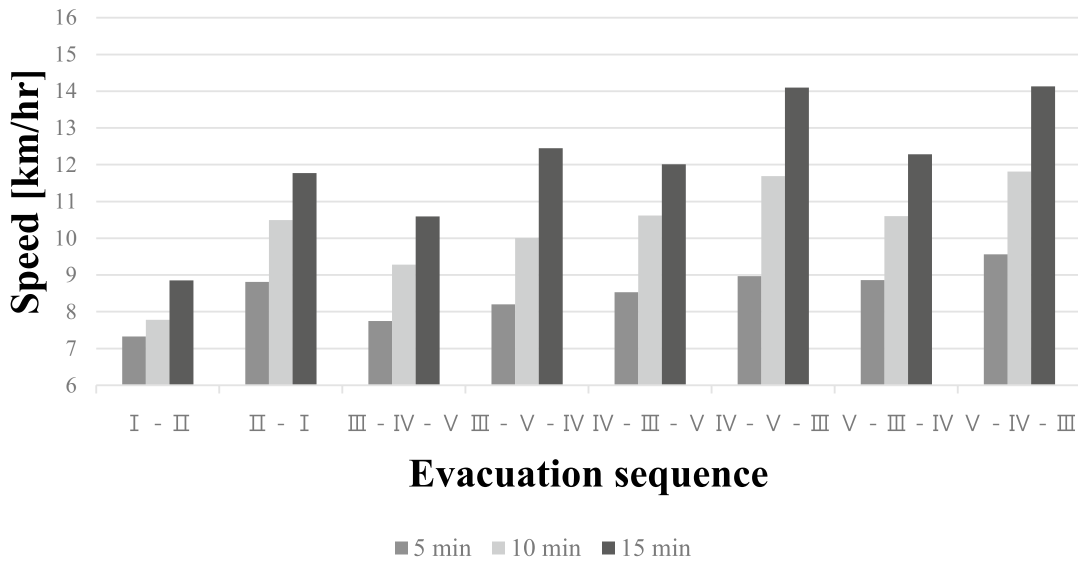

Fig. 7 Average speed of each evacuation sequence as the evacuation start time interval increases

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