Platform for Radiological Emergency Agent-based Integrated Simulation Model Updated for Relief Process

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1. Introduction

Nuclear power plants are equipped with five protective barriers to prevent the leakage of radioactive materials. The importance of the containment, which is the final barrier, was realized during the Chernobyl accident, and the damage from that event has yet to be fully recovered. Such is the magnitude of the long-term and widespread complexities caused by the release of radioactive substances. We have previously introduced the PRISM (Platform for Radiological Emergency agent-based Integrated Simulation Model) through several papers, which is an evacuation simulation based on an agent-based model during radiological emergencies [1]. In PRISM, agents are represented as residents, moving according to certain rules defined by algorithms. PRISM describes the behavior of residents during a radiological emergency, allowing the optimization of relief supplies, evacuation routes, shelter locations, and evacuation scenarios.

The previous PRISM was designed to observe how much residents are exposed to radioactive substances during their evacuation to emergency shelters. However, it had limitations of oversimplified behavior of radioactive materials, and the ignorance of irregularities that could affect the movement of residents during the evacuation process. In this study, the behavior of radioactive materials is depicted using the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) software, which calculates the Lagrangian multi-particle concentration. Moreover, the movement of agents has been variably configured by adding infrastructure elements, which can control the evacuation process, such as communication, medical, service, or police.

2. Overview of PRISM

To minimize the damage from radiation accidents, radiological emergency preparedness and response (EPR) plan must be established. PRISM is an integrated modeling framework that uses Agent-Based Modeling (ABM) to consider the interactions and behaviors of individual elements related to radiation emergencies. ABM is used to reproduce and predict complex phenomena. The location and operation of agents are encoded in the form of computer program algorithms. Multiple agents, following certain rules, move with simple behaviors, interact with each other, and lead to complex behaviors that change the state at the overall system level. Due to its accessibility and easy programming language, the free software Netlogo is one of the common tools for ABM. PRISM focuses on demonstrating the emergency modeling process by describing complex interactions in emergency situations. In addition, importance analysis has been performed to identify the effects of shelter functions and to capture which shelters are important.

Borrowing the underlying concept of resilience, it was customized as the probability that the recovery degree (RES) goes back to its original or required level (REC^*) within required time t . It's assumed that REC is influenced by hazard elements and infrastructural elements. Fig. 1 shows that the attributes of elements are determined by interaction. For example, the exposure (i.e., health conditions) of evacuee increases by the concentration of radioactive material and may decrease by relief supplies. It is determined by various factors and attributes such as location, speed, and concentration.

Fig. 2. shows a schematic of PRISM. The procedure of PRISM is as follows. Firstly, environment modeling for a target area is performed. Road networks, buildings, and infrastructural resources are modeled by using GIS data. Second, depending on the scope of the simulation, identify and select elements of protection targets, hazard, and mitigation infrastructure. Third, path-finding, traffic, and atmospheric dispersion model are selected to reflect interactions. Finally, $REC$and $RES(t)$ are analyzed with multiple simulations [2].

3. Updated features of PRISM

3.1. Additional and Advanced Models

The previous version of PRISM considered the availability to distribute relief supplies at shelters and the number of buses as infrastructure elements and attributes. To consider more diverse infrastructure elements and their corresponding attributes, advanced infrastructure modeling was applied. While the Gaussian Puff model was used as the atmospheric dispersion model in PRISM, considering its extensibility, we implemented a method to import the results of the HYSPLIT software, which enables Lagrangian multi-particle concentration calculations.

3.1.1 Infrastructure

Infrastructure plays an important role in saving lives during disasters and ensures a quick recover of the society. The term "infrastructure" refers to the basic physical facilities and services necessary for a society or economy to function normally. In a broader sense, this can also include public health facilities, educational institutions, housing, and parks. These facilities support societal stability and economic growth and enhance individuals' quality of life. Especially in the case of radiological emergencies, which can be more damaging than other types of calamities, the role of infrastructure is emphasized even further. In the event of a radiological emergency, unlimited resources can't be deployed, and overinvesting resources can even backfire. Therefore, the PRISM emergency evacuation simulation can try whether that systems operate efficiently and are managed well when infrastructure is limited, allowing for the establishment of ideal evacuation plans and optimization of disaster responses.

To quantitatively understand the abstract concept of "infrastructure," we referred to the Cascading Effect [3] and the NSSC's (Nuclear Safety And Security Commission) standard manual. There are 22 types of infrastructures, and we chose 'transportation', 'medical', and 'communication' among them, as they are physically affected during a radiological emergency. In PRISM, infrastructure doesn't operate as a new agent; instead, it systematically exists to affect the variables that agents possess. Infrastructures influence other infrastructures and the residents. The transportation infrastructure ensures safe evacuation for people, thus effective traffic management and congestion prevention strategies are essential during disasters. Medical infrastructure plays a role in maintaining people's health and saving lives during a radiological emergency. Communication infrastructure is pivotal in swiftly conveying disaster information and broadcasting evacuation directives. Effective communication smoothens the evacuation, ensuring its successful completion. In PRISM, transportation infrastructure controls moving vehicles to prevent traffic congestion and increases the maximum road speed to minimize traffic jams. Medical infrastructure influences the rate at which supplies are distributed to evacuees which arrived at shelters. Evacuation doesn't end upon reaching the shelter; it is complete once evacuees receive supplies, so the rate of recovery varies depending on the amount of medical infrastructure available. The communication infrastructure, by randomly altering the variables of agents, results in situations where residents might not receive disaster information, resulting in delayed or misdirected evacuations. We abstracted and formulated the above concept to implement ABM environment as flexibly as possible, below:

$$\Delta \boldsymbol{w} = C \times \boldsymbol{i}$$

$$\begin{bmatrix} \Delta w_1 \\ \Delta w_2 \\ \vdots \\ \Delta w_m \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & & \\ c_{21} & c_{22} & c_{23} & \cdots & \\ c_{31} & c_{32} & c_{33} & & \\ & \vdots & & \ddots & \\ & & & & c_{mn} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_n \end{bmatrix} \quad (2)$$

Inputs:

$\boldsymbol{I} = Vector\ of\ infrastructure, \boldsymbol{I} \in R^n$
$\boldsymbol{i} = Vector\ of\ normalized\ infrastructure, \boldsymbol{i} \in [-1, 1]\ , \boldsymbol{i} \in R^n$

$\boldsymbol{A} = Vector\ of\ global\ attribute, \boldsymbol{A} \in R^m$
$C_{m\times n} = Matrix\ of\ relationship$
$between\ infrastructure\ and\ global\ attribute$
$\Delta\boldsymbol{w} = vector\ of\ the\ variation$
$of\ the\ global\ attribute,\ \Delta\boldsymbol{w} \in R^m$

Objective Function:

$T_{end} = f(A(\boldsymbol{i}), S(t), H(t))$
$\vec{\iota}^* = \underset{\boldsymbol{i}}{\operatorname{argmin}} T_{end}$

Constraints:

$\sum_{x=1}^{m} d_x I_x = constant$

Infrastructure vector $\boldsymbol{I}$ consists of n elements such as police, medical, communication, etc., that influence the global attribute influencing the entire evacuation situation. These represent actual resource quantities, so they hold values greater than or equal to zero. One example is below: For instance, if $I_{police} = 200$, then there are 200 deployed police officers, which in turn elevate the speed limit, a global attribute of the roads. The normalized infrastructure vector $\boldsymbol{i}$ ranging from -1 to 1 dictates the increase or decrease in the global attribute. $\boldsymbol{A}$ stands for the global attribute vector with m elements. In this study, variables influencing the PRISM system such as road speed limits, supply speed, and communication availability were selected. C represents the $m \times n$ matrix that shows the relationship between infrastructure and global attributes, where each element can vary from negative infinity to infinity. The relationship of the global attribute is assumed to be linear. Eq. 2 means $\Delta\boldsymbol{w}$ is defined as the product of C and $\boldsymbol{i}$, and is computed every dt to update the global attributes. For example, if w_1 is 0.2, then the road's speed limit will increase by 20%, facilitating faster evacuation.

The constraint is set where the sum of costs remains constant. To minimize disaster damages, the government will deploy all available human and material resources. This implies that resources are limited, and there's also a risk of excessive resource deployment leading to wastage. In an emergency evacuation scenario, where resources need to be allocated in a short time span, maintaining a constant sum of costs translates to optimal resource distribution. Weights $\boldsymbol{d}$ are set according to the operational difficulty and importance of each infrastructure. Multiplying the infrastructure vector $\boldsymbol{I}$ by these weights results in a constant sum, termed as cost. The maximum resources the government can deploy is set as user's intent. In this study, the deployment of infrastructure is assumed to be varied over time. At the onset of evacuation, there'd be a higher demand for police than medical personnel. As the evacuation progresses, the need for medical staff to tend to evacuees will increase. For the three infrastructures, one is kept constant, one increases over time, and one is deployed only at specific times, dividing into three cases. This allows us to observe which deployment case optimally facilitates evacuation while satisfying constraints. Thus, the objective function becomes the minimization of the evacuation completion time. The evacuation end time T_{end} is determined by $A(\boldsymbol{i}), S(t), H(t)$. The $H(t)$ value represents the exposure level of the agents, and it is assumed that the agent was exposed based on the dose calculation of HYSPLIT for the ground exposure level.

To optimize the infrastructure, PRISM is run with x^n combinations of infrastructure according to number of infrastructure (n) and type of infrastructure change (x).

$$\overrightarrow{\boldsymbol{A_{t+1}}} = \begin{bmatrix} \boldsymbol{A_{1,t}(1 + \Delta w_{1,t})} \\ \boldsymbol{A_{2,t}(1 + \Delta w_{2,t})} \\ \vdots \\ \boldsymbol{A_{m,t}(1 + \Delta w_{m,t})} \end{bmatrix} \tag{3}$$

Equation 3 means updating $\Delta\boldsymbol{w}$, calculated with an appropriate $\boldsymbol{I}$ under the constraints, to PRISM in accordance with the dt and multiplying it with the global attribute $\boldsymbol{A}$. Meanwhile, $\boldsymbol{A}$ has maximum and minimum values determined by the limits set within PRISM. Therefore, T_{end} is determined, and the optimization of infrastructure can be found through numerous trials of PRISM. In this study, the values of C and $\boldsymbol{d}$ were arbitrarily set, but appropriate values will be used in the future based on further research and data collection.

3.1.2 Connection with HYSPLIT

The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model is a computer model used to determine the direction and distance of atmospheric pollutant movement by calculating air trajectories. It can compute backward trajectories/deposition and concentration of pollutants. HYSPLIT was developed in 1982 by the NOAA (Atmospheric Resources Research Lab of the U.S. National Oceanic and Atmospheric Administration) to assess the impacts of nuclear fallout during the Cold War. The current HYSPLIT 4 computational code, with advancements in computing capabilities, is now able to process three-dimensional meteorological data from multiple grids. This model can be applied to emergency response events such as real-time forest fire smoke prediction, radioactive material tracking and prediction, and yellow dust by analyzing the relationship between various air pollutants and source-receptors.

Previous PRISM applied the Gaussian puff model to describe the trajectory of radioactive materials. The Gaussian model provides reasonable and swift information on air concentration, deposition, and dose with relatively limited data. However, the Gaussian puff model has limitations in that its evaluation distance from the accident nuclear power plant is up to 160 km, and it can accurately describe scenarios only in calm or light wind conditions. The Lagrangian dispersion model, which utilizes meteorological data inputs such as wind direction, wind speed, atmospheric stability, and rainfall, is more time-consuming and complex compared to the Gaussian puff model. However, it can evaluate distances from tens of meters up to several hundred kilometers, leading to the adoption of the HYSPLIT model [4].

In this research, radioactive material emission rates and nuclides are referenced in the HYSPLIT tutorial. Meteorological data were sourced from the NOAA website, specifically downloading the GFS 0.25 Degree dataset. As pollutants, Cs-137 and I-131 were selected, with 500 particles being released every hour. We set the concentration grid resolution to 0.005 to ensure high resolution. Upon model completion, the concentration tab calculates the Dose (Sv) based on radioactive material concentration tool. This tab generates files in the working directory that include the top 10 radioactive isotopes contributing to short-term exposure. The converted result files can be visually represented as dose-specific contours through a visualization module. The result files are extracted in a shapefile format and are updated in PRISM every minute. Figure 3 displays the HYSPLIT result files in PRISM. When an Agent intersects with a contour, its exposure level shifts to correspond with that specific dose.

4. Conclusions

In this study, we introduced the improved PRISM model for evacuation simulations during radiological emergencies. The previous version of PRISM had limitations, such as oversimplified behavior of radioactive materials, and the ignorance of irregularities that could affect the movement of residents during the evacuation process. To overcome these limitations, the HYSPLIT model was integrated to the previous model of PRISM to depict the behavior of radioactive materials. Additionally, infrastructure elements like the police were added to control the evacuation process. The HYSPLIT model calculates air trajectories and can be applied to emergency response events, such as tracking radioactive materials. This overcomes the limitations of the previously used Gaussian puff model. Infrastructure plays a crucial role in saving lives during disasters. This study emphasizes the importance of transportation, medical, and communication infrastructure during radiological emergencies.

Evacuation during radiological emergencies is a critical process, and optimizing infrastructure is essential. In this study, we simulated various infrastructure combinations using the PRISM model. The goal is to use limited resources most effectively to ensure the safety of as many people as possible. As a result, PRISM creates an appropriate combination and arrangement of infrastructure, significantly enhancing the success rate of evacuation during radiological emergencies. Future research plans to refine this by applying appropriate interrelationships between infrastructures and weights for evacuation.

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Appendix

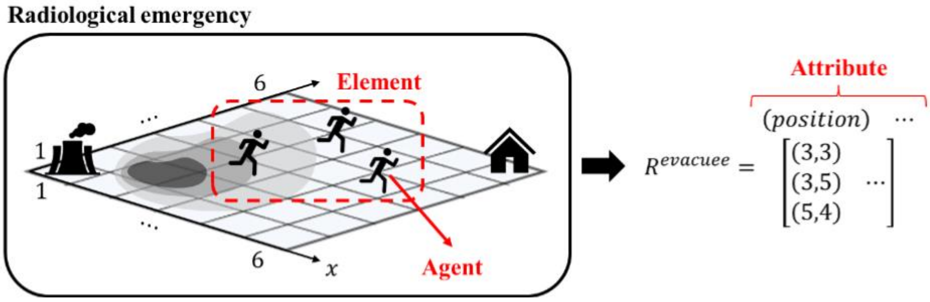

Fig. 1. Systemization of radiological emergency

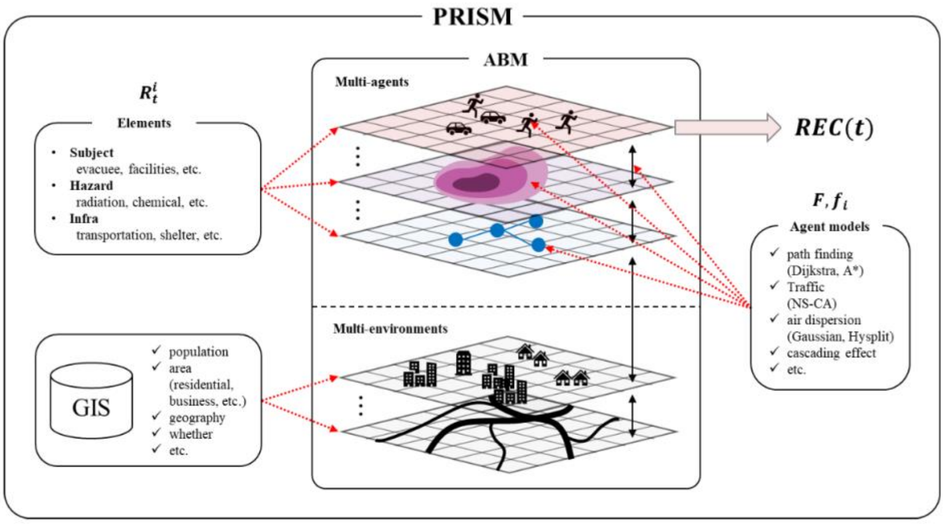

Fig. 2. Schematic diagram of PRISM

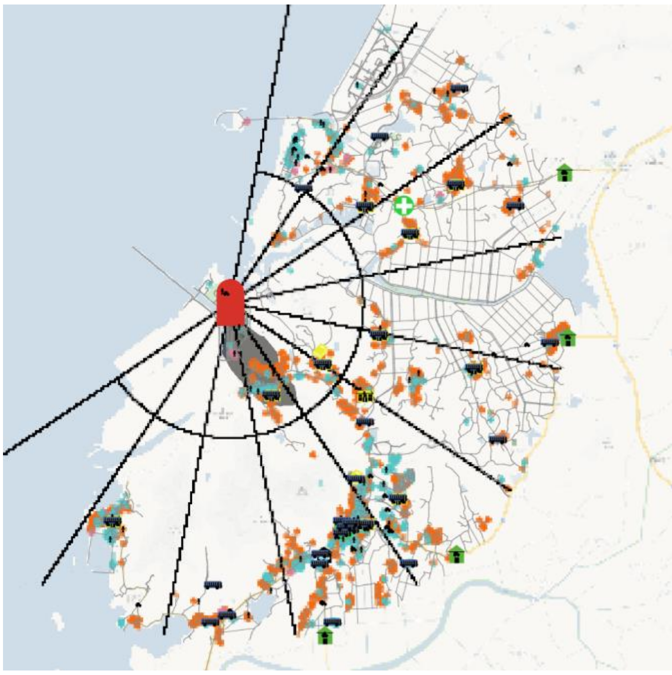

Figure 3. HYSPLIT result file applied to PRISM [5]