An Approach to Estimating the Frequency of Forest Fire-induced Loss of Offsite Power using Cellular Automata with GIS Data

Kyungho Jin [a], Yong Hun Jung [a], Dong-San Kim [a]
[a] *Korea Atomic Energy Research Institute, Daejeon, Republic of Korea*
[*] *Corresponding author: jungyh@kaeri.re.kr*

***Keywords:** Forest fire, Probabilistic Safety Assessment, Cellular Automata, Geographic Information System

1. Introduction

As the frequency and scale of forest fires has recently increased worldwide, many efforts have been made to evaluate how forest fires affect the safety of nuclear power plants (NPPs). One of the efforts is to assess the risk of forest fires as an external event through probabilistic safety assessment (PSA). The Korea Atomic Energy Research Institute (KAERI) has proposed a comprehensive external event PSA framework for a forest fire, which includes the analysis of their frequency, behavior, and the impact on the plant inside as well as the plant response strategies [1].

According to [1], it is essential to analyze the forest fire frequency and their consequences to figure out the characteristics of initiating events triggered by forest fires. Typically, loss of offsite power (LOOP) event is one of the main concerns for external event PSA for forest fires. This is because a forest fire increases the likelihood of damage to transmission lines. Despite the significance of LOOP events, obtaining actual cases of forest fire-induced LOOP occurrences is challenging due to their rarity in observations.

To handle this challenge, previous studies have incorporated forest fire simulations such as FARSITE, which is a vector-based scheme, into PSA to explore the relationship between forest fires and NPPs [2, 3]. While these vector-based simulations can offer the advantage of investigating specific information about forest fire, but they have the drawback of high computational costs required for calculations: it is difficult to consider all possible scenarios of forest fires within the area of interest, depending on the initial forest fire location or the direction of spread.

Another way to describe forest fire behavior is a raster-based method that involves dividing the area of interest into multiple cells or lattices and probabilistically determining the state of each cell according to specific rules [4]. Cellular automata (CA) are widely used to implement the raster-based method for forest fire spread [5]. Using CA could be more suitable for describing a large number of forest fire scenarios because of its low computational cost.

Therefore, this study proposed the framework to analyze the forest fire-induced LOOP, especially their frequency, using raster-based cellular automata to consider as many different forest fire scenarios as possible. It should be noted that the purpose of this paper is to introduce the details for each element of the proposed method and the detailed results of its application will be dealt with in the next research.

2. Forest fire-induced LOOP frequency using the raster-based simulation

2.1. Forest fire-induced LOOP frequency

Forest fires, as external hazards to NPPs, are closely related to LOOP event because they are likely to cause damage to transmission lines. To calculate the frequency of forest fire-induced LOOP due to loss of transmission lines, the concept of the conditional probability is proposed in this paper. Here, the conditional probability refers to the probability of forest fires causing LOOP events when they occur. Therefore, estimating the forest fire-induced LOOP frequency is divided into two steps: evaluation of the frequency of forest fires themselves and evaluation of the conditional probability.

In general, the forest fire frequency can be represented according to their severity (e.g., intensity) because the impact on transmission lines varies depending on the level of severity. While a forest fire intensity is widely used as a prominent severity indicator [2, 3], it does not account for the initial location or spread direction of forest fires. Therefore, this paper attempts to employ the area damaged by forest fire (hereinafter *damaged area*) as a severity of hazards. Especially, using CA, it allows for comprehensive consideration of the severity of forest fire for various scenarios.

Consequently, as shown in Figure 1, the forest fire frequencies in South Korea over the past 10 years can be depicted depending on the damaged area, which is divided into several bins.

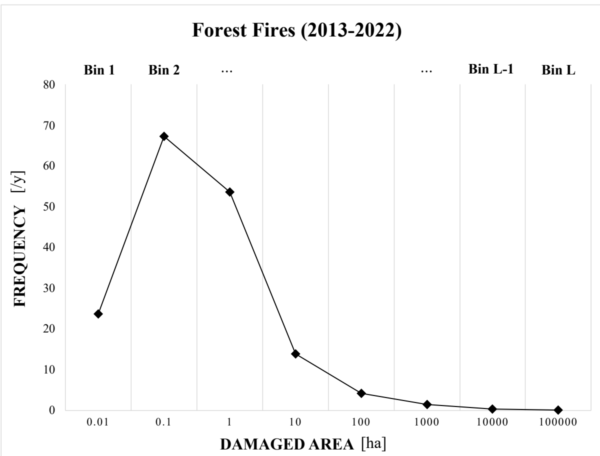

Fig. 1. Forest fire frequency depending on the damaged area [ha] in Korea

The records of forest fires based on the damaged area presented in Figure 1 can be easily accessed from the Korea Forest Service [6]. Accordingly, once we can determine the conditional probability p of forest fires causing LOOP for each bin as shown conceptually in Figure 2, deriving the frequency of LOOP events due to forest fires becomes straightforward.

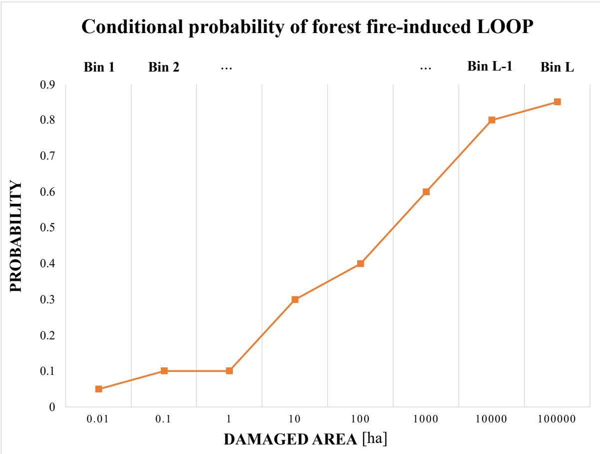

Fig. 2. An example of the conditional probability depending on the damaged area due to forest fire

The forest fire-induced LOOP frequency using the historical forest fire frequency f and the conditional probability p is:

$$F_{Bin[i]} = f_{Bin[i]} \times p_{Bin[i]} \qquad Eq.\ (1)$$

Where, F is the forest fire-induced LOOP frequency [/y], f is the historical forest fire frequency [/y] depending on the damaged area, and p is the conditional probability [-] of forest fire initiating a LOOP depending on the damaged area.

In Eq. (1), f can be simply obtained through forest fire data recorded over a specific period as shown in Figure 1. On the other hand, it is challenging to determine the conditional probability p in Eq. (1). The next section describes a detailed method for estimating this conditional probability.

2.2 How to estimate the conditional probability using rater-based simulation

The key idea proposed in this paper is to simulate as many forest fire spread scenarios as possible to investigate whether forest fires affect areas where transmission lines are located. In other words, if out of a total of N possible forest fire scenarios that can occur in the area of interest, and the number of c forest fire scenarios spreads to the location of the transmission lines, then the conditional probability p is given by:

$$p_{Bin[i]} = \frac{c_{Bin[i]}}{N} \qquad Eq.\ (2)$$

Where, p is the conditional probability of forest fire causing LOOP, c is the number of cases where transmission lines are damaged by forest fire, and N is the number of total simulations.

Since forest fire spread is determined by factors such as prevailing wind direction, wind velocity, humidity, and so on, a large number of simulations are required to take all these conditions into account.

For this reason, a raster-based forest fire simulation method is employed in this paper. Ultimately, the goal is to find the number of scenarios in which a forest fire spreads to cells where transmission lines are located.

2.2.1 Raster-based simulation: cellular automata

Raster-based simulation is a method of analyzing the area of interest by dividing it into several squares or hexagons. In particular, cellular automata are used to determine the state of each cell probabilistically based on the various spread rule. In cellular automata, determining the state of cells located in the Moore neighborhood of a cell ($s^k_{i,j}$) is a major concern (See Figure 3). The state of each cell can have a total of k finite states.

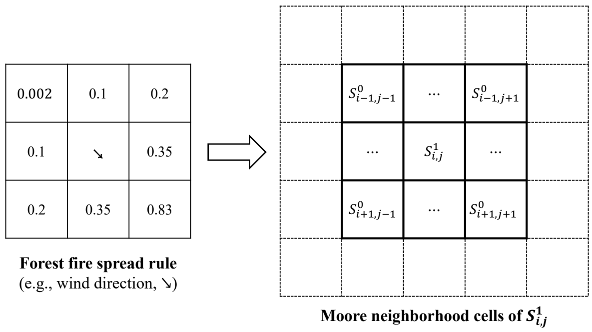

Fig. 3. An example of forest fire spread rule and Moore neighborhood cells of $S^1_{i,j}$

Suppose that each cell can have two states: *damaged* (k=1) and *undamaged* (k=0). Let's consider the scenario where a forest fire occurs at the i, j-th cell ($s^1_{i,j}$). The forest fire will spread to Moore neighborhood cells probabilistically according to the forest fire spread rule, which consider various environmental conditions, as shown in left of Figure 3.

For example, if the prevailing wind direction is southeast, the state of the cell ($s^k_{i+1,j+1}$) is determined with $P\left(s^0_{i+1,j+1} \rightarrow s^1_{i+1,j+1}\right) = 0.83$. These spread rules should be constructed to describe actual forest fire behavior through actual weather data in area of interest, expert judgment, or GIS data. More detailed research on the spread rule will be conducted in the future.

By determining the status of all cells according to preset rules and repeating this process several times, it is possible to depict how a forest fire spreads from its initial point of origin.

2.2.2 How to estimate the conditional probability of forest fires causing LOOP using CA

The basic concept for calculating conditional probability using CA is shown as Figure 4. The cell in red indicates the damaged area due to forest fire. When CA is performed with the damaged area of 5, the forest fire does not affect the target cell (e.g., transmission line) in case of (a), (b), and (d). On the other hand, in case (c), the target cell is definitely damaged by forest fires. Therefore, if a total of 4 CAs were performed, and one case affected the target cell, the conditional probability would be evaluated as $p_{Bin[5]} = 0.25$.

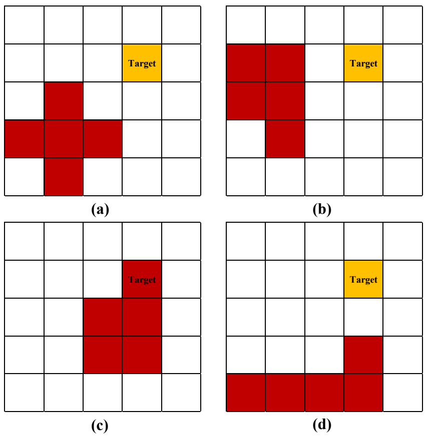

Fig. 4. Four examples of CA for forest fire spread to evaluate the conditional probability, $p_{Bin[5]}$

2.3. CA on GIS data and Monte Carlo simulation

In practice, forest fires cannot spread to all areas (or cells) because there are non-forested areas, such as fire lines, within the area of interest. Therefore, it is necessary to determine the initial state of each cell using geographic information system (GIS) data. GIS is a system for storing, managing, and analyzing geographical and spatial information. It includes information about forests, so it can be said to be essential data for analyzing forest fire behavior. Since GIS is widely used in various industrial fields, detailed explanations will be omitted in this paper. Consequently, performing CA using GIS data involves the following procedures.

(a) Set target area and import GIS data for target area;
(b) Partition target area into m cells;
(c) Determine the state of cells using GIS data and the target cells (e.g., target in yellow in Fig. 5);
(d) Perform CA according to forest fire spread rules.

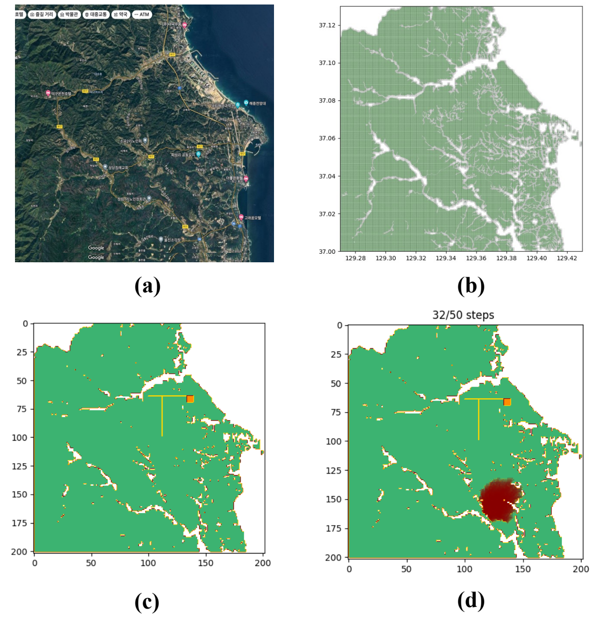

Fig. 5. The procedure to perform cellular automata on GIS data

In addition, it is necessary to combine the Monte Carlo simulation (MCS) with CA to simulate forest fire spread under various input conditions (e.g., initial forest fire location, and so on). Table 1 shows the overall procedure of the proposed method to calculate the conditional probability p, written in pseudocode.

Table I: Pseudocode for calculating the conditional probability, p

Pre-processing	**Import** GIS data for target area **Partition** target area into m cells **Determine** cell state ($\boldsymbol{S_{i,j}^k}$) using GIS data **Determine** target cells e.g., transmission line, site, … **Determine** forest fire spread rules e.g., wind direction, fuel, …
BIN **MCS** **CA**	**For** (w=1 to L) **For** (d=1 to N) **Select** initial fire cells (randomly) **Select** spread rules (randomly) **Perform** CA until $\boldsymbol{B_A == Bin\ [w]}$ **If** (any target cell is damaged), **Then** $\boldsymbol{c_{Bin[w]}}$ += 1 $\boldsymbol{p_{Bin[w]}} = \frac{\boldsymbol{c_{Bin[w]}}}{\boldsymbol{N}}$

3. Conclusions

In this paper, we proposed a method of estimating forest fire-induced LOOP frequency using the concept of conditional probability. Specifically, CA, a raster-based method, was used to estimate the conditional probability, and the overall procedure for incorporating CA into GIS data with MCS was described.

In the next study, it is necessary to determine the boundaries of the area of interest, the size of each cell, and the definition of spread rules using actual data. Using this result, the frequency of forest fire-induced LOOP should be evaluated and integrated into external event PSA framework.

Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using financial resources granted by the Nuclear Safety and Security Commission (NSSC) of Korea (No. RS-2023-00240452).

REFERENCES

[1] Korea Atomic Energy Research Institute, "Status Analysis and Strategic Planning for the Development of External Fire PSA Technologies", KAERI/TR-9877/2023 & NSTAR-23NS11-322, 2023

[2] Okano, Y. et al., Hazard Curve Evaluation Method Development for a Forest Fire as an External Hazard on Nuclear Power Plants, *Journal of Nuclear Science and Technology*, **53**, 1224-1234, 2016

[3] J. Lim et al., Study on the Loss of Off-site Power Frequency under Forest Fire, Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, Oct. 26-27, 2023

[4] C. Diaz-Avalos, et al., Modeling the Spatial Evolution Widlfires using Random Spread Process, *Environmetrics*, **33**, 2022

[5] S. Yassemi, et al., Design and Implementation of an Integrated GIS-based Cellular Automata Model to Characterize Forest Fire Behaviour, *Ecological Modelling*, **210**, 71-84, 2008

[6] Korea Forest Service. 2022 Annual Report on Forest Fire Statistics (in Korean), 2023