A Study on Evacuation Time Estimation for Offsite Consequence Analysis Using Agent-Based Modeling

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EXTENDED ABSTRACT

The offsite consequence analysis of nuclear power plants represents a critical component of Probabilistic Safety Assessment (PSA), evaluating both early and long-term impacts on residents following accidents involving radioactive material release. The MACCS (MELCOR Accident Consequence Code System), developed by Sandia National Laboratories (SNL), serves as the representative computational tool for conducting comprehensive offsite consequence analysis within the Level 3 PSA framework.

The current MACCS protective action modeling approach maintains safety margins through conservative assumptions while achieving computational efficiency through simplified models. However, this approach has inherent limitations due to highly simplified evacuation scenarios and static timetables that highly depend on expert judgment for determining resident accident awareness time (alarm time), sheltering duration, and evacuation timing. Although detailed configurations are possible, such as subdividing cohorts to establish cohort-specific scenarios or setting evacuation speeds for individual sections within the Emergency Planning Zone (EPZ), establishing scientific basis for these detailed parameter values remains challenging.

This study presents a methodology to address these limitations through Agent-Based Modeling (ABM) approach for protective action modeling and simulation, along with the development of a comprehensive software tool. ABM provides a computational approach for predicting macroscopic system behavior through microscopic agent interactions, enabling more realistic protective action modeling by incorporating spatial heterogeneity, individual behavioral variations, and dynamic interaction effects.

The ultimate goal of this study is to integrate the ABM into the existing Level 3 PSA framework by utilizing the results of agent-based protective action simulation as inputs for MACCS. In other words, while maintaining the well-established Level 3 PSA framework, this study aims to provide more detailed and realistic inputs for the protective action modeling stage, thereby enhancing the scientific basis and validity of offsite consequence analysis results.

The key input variables constituting MACCS protective action modeling are structured as follows:

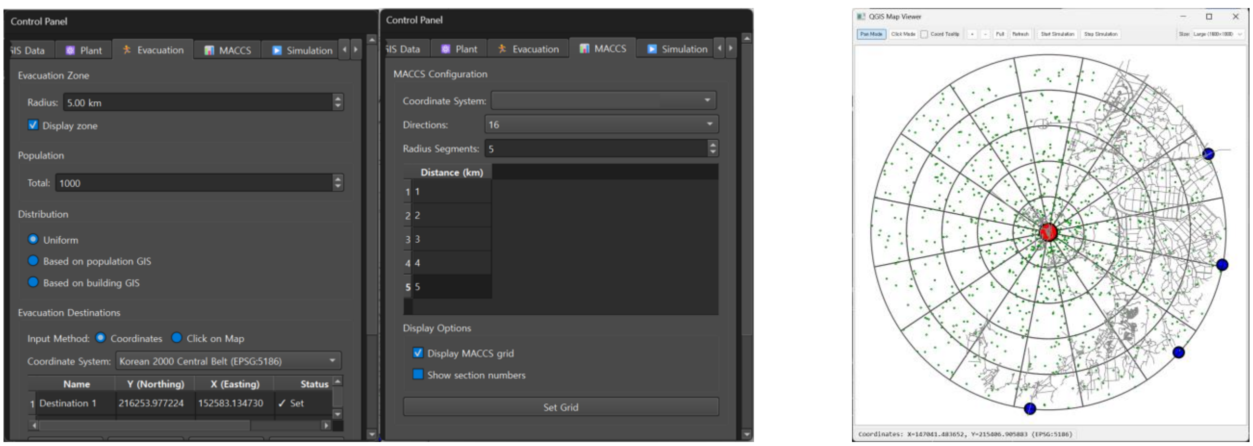
TABLE I. Key variables of MACCS protective action modeling

Variable Name	Data Type	Data Dimension	Description
Population	integer	[nCohort][nDirection][nRadius]*	Population distribution for each section (grid)
DURBEG & DURMID	integer	[nCohort]	Duration of Evacuation 1 (DURBEG) and Evacuation 2 (DURMID) for each cohort
ESPEED	float	[nCohort]	Evacuation speeds for each cohort in Evacuation 1, 2, and 3 sections (in m/s)
Network evacuation direction	integer	[nCohort][nDirection][nRadius]	Network evacuation direction for each section (1: outward, 2: rightward, 3: backward, 4: leftward)
Network evacuation speed	float	[nCohort][nDirection][nRadius]	(Optional) Speed multiplier for each section
DLTSHL	float	[nCohort][nRadius]	Delay time to sheltering for each cohort and each radius
DLTEVA	float	[nCohort][nRadius]	Delay time to evacuation for each cohort and each radius

(* nCohort: number of cohorts, nDirection: number of directions, nRadius: number of radii)

The developed agent-based protective action simulation tool basically incorporates Geographic Information System (GIS) data to represent realistic spatial configurations and consists of numerous agents simulating resident evacuation behavior. GIS data primarily requires road network information, while residential, commercial, and tourist area distributions, along with population distributions, can be effectively utilized. Resident agents implement pathfinding models for predicting routes to evacuation destinations and traffic models for predicting evacuation speeds considering traffic congestion and interactions with other agents. Real-time data such as evacuation speeds and routes generated from ABM simulations are reprocessed and clustered to provide inputs for MACCS protective action models. For the clustering, K-Means is used. However, Given the complex, multi-dimensional nature of evacuation data, non-linear, multi-dimensional clustering methods such as OPTICS are also being considered for future refinement.

To accomplish this, a prototype program has been developed as shown in the figures. The program's main functions include GIS data processing, agent-based evacuation simulation incorporating pathfinding and traffic models, simulation visualization, simulation result processing and conversion to MACCS input data, and graphical user interface capabilities. Figure 1 (a) presents portions of the program's key inputs. The left panel shows evacuation simulation settings that enable more realistic simulations by utilizing GIS data to configure population distributions and evacuation destinations. The right panel displays settings related to MACCS input conversion. Figure 1 (b) presents the GIS data-based simulation visualization window, which provides intuitive understanding of evacuation route and speed behaviors through visualization.



(a) (b)

FIGURE 1. Developed prototype program

The developed methodology can provide a more reasonable foundation for protective action model inputs in Level 3 PSA applications. Fine-tuning of MACCS inputs through ABM simulation results enables more realistic and valid analysis outcomes. Future work will focus on conducting MACCS sensitivity analyses using various ABM simulation-based inputs to improve MACCS input conversion methodologies. Additionally, the methodology will be expanded to incorporate additional behavioral factors, weather conditions, and infrastructure variations that influence evacuation effectiveness under diverse emergency conditions. This comprehensive approach will enhance the scientific basis for nuclear emergency preparedness and risk assessment activities.

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