Proposal to Estimate the Mobile Equipment Installation Time during a Multi-unit Accident Management using an Agent-Based Model

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1. Introduction

PSA (probabilistic safety assessment) technique was developed to realistically estimate the risk of the commercial NPPs (nuclear power plants) in order to gain insights for improving the plant safety (for example, allowing establishment of effective actions and barriers to prevent accident progressions). However, where there are multiple NPPs on a single site, traditional single-unit PSAs are not enough.

During beyond design-basis extreme external events such as earthquake, wildfire, or tsunami (hereinafter referred as *extreme events*), multi-unit accidents may occur. In such a case, various accident management organizations will be launched, with their personnel to be summoned (from hereinafter *convocated*) from outside the plant site. These organizations and workers may work in an inter-unit level, and these inter-unit dependencies must be assessed for better estimating the realistic risk of commercial plants. In other words, MUPSA (multi-unit PSA) need to be performed to gain better site-level insight and improve multi-unit accident management guidelines.

Since there are so many uncertainties regarding arrival of the workers from off-site and installing mobile equipment on-site, the U.S. and the Korean multi-unit accident management guidelines assume off-site workers are unavailable for the first 6 hours of the accident progression [1,2]. However, if time distributions can be simulated for 1) the off-site personnel convocation and 2) the on-site mobile equipment installation, the results can be used for HRA (Human Reliability Analysis) to ultimately better estimate the NPP risk in the MUPSA.

Purpose of this research is to propose a way to estimate the time distribution to transport and install the mobile equipment by the inter-unit convocated off-site workers using the ABM (agent-based modeling). In the future, simulated ABM results for the on-site mobile equipment time distribution can be combined with the results of the off-site worker convocation time distribution [3] for multi-unit HRA and ultimately MUPSA.

2. Current Assumption on Off-Site Workers during Extreme Events

Since the Fukushima accident, many countries around the world employed additional accident management strategies to utilize inter-unit mobile equipment (e.g. U.S. FLEX and Korean MACST) for flexible accident response in case of an extended loss of AC power and a loss of ultimate heat sink accident [1, 2]. Unlike single-unit accidents where operators and field workers from each unit manage the accident, multi-unit accidents involve shared human resources and equipment. There are inter-unit organizations, and convocated off-site field workers may transport and install the mobile equipment from SC (Safety Center) to the required reactor units [3].

However, these organization's personnel and field workers must arrive from outside the NPP site to the required on-site locations, before they can become functional. Since there is no data (both experiments and simulations) on how long the off-site workers would take to arrive on-site during extreme events, it is stated in the AMP (accident management plan) that the on-site workers would manage the multi-unit accident (including installing mobile equipment) themselves during the early stages of multi-unit accidents caused by external events, assuming off-site workers will not arrive on site within first 6 hours of the accident progression to transfer and install the mobile equipment [4].

These assumptions, however, may not hold true during extreme events. If more than minimum number of off-site workers required to move a mobile equipment are convocated on-site (i.e. minimum number of required staffing level is reached), then these workers may join the accident management and go right into the installation of the mobile equipment (i.e. they will not just seat around).

If the mobile equipment installation time distribution can be found through experiments, then the regulators and NPP companies can gain better insights to see if the current guidelines are truly conservative or not conservative enough. The AMP may then be revised to better represent the multi-unit accident management situation.

Unfortunately, it is impossible gain experimental data for NPP operators, organizations, and off-site workers for the extreme external events since such events are almost never expected to occur. Nonetheless, simulation models can be developed to better estimate the mobile equipment installation time distributions for better insights on extreme events accident management. Through simulation, one can estimate the delay or even failure for timely mobile equipment installation for multiple units. The convocation time to arrive will differ for each worker (hence the need to find distributions instead of point estimation). This study propose using ABM to assess the feasibility (or infeasibility) of performing required tasks by convocated off-site workers for on-site mobile equipment installation.

3. Equipment Installation Estimation using the Agent-Based Model Behavioral Rules

3.1. Monte-Carlo Agent-Based Model (MCABM)

ABM is a bottom-up computation model where complex macroscopic phenomena of the system is simulated through actions and interactions of the microscopic autonomous entities, called *agents*. Each agent (for example, an off-site convocated worker) has attributes with programmed individual behavioral rules (functionalities and/or models) that determine the values of these attributes and decision-making during interactions with different agents in an environment. Each agent interacts as distinct part of simulation. Through microscopic behavior of each agents and with their interactions, macroscopic behavior of the system is observed [3,5]. Figure 1 shows a representation of how agents and their behavioral rules contribute to the macroscopic system's emergent behavior. For the mobile equipment installation simulation, agents may be off-site convocated workers who have arrived on-site or specific mobile equipment (such as 1MW mobile generator or portable low-pressure pump).

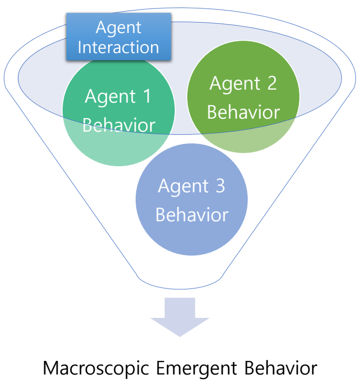

Fig. 1. Macroscopic System Behavior Emerging from Microscopic Agent Interactions

Difficulties exist in choosing what would be realistic values of the parameters used for the behavioral rules for each agent if they cannot be found experimentally. For example, maximum speed of transporting the equipment inside the NPP site may need to account for time of the day (if outside is dark, then the transportation time may take longer), road conditions, weather, etc. Easiest way to overcome this problem is to assume minimum and maximum values to use random Monte Carlo (MC) sampling. As in previous research for simulating off-site workers convocation time through Monte-Carlo Agent-Based Model (MCABM) [3], simple MC sampling and/or Latin hypercube sampling method can be used to simulate the time distributions for the mobile equipment installation (including transportation).

3.2. Proposed Equipment Installation Rate based on Staffing Level

During extreme events, unless all the required personnel for multi-unit accident management live on-site, accident responses will start from the off-site workers assessing the situation, preparing for departure, and leaving their homes to get to the NPP site [6]. Unlike during safety drills in the NPP sites, these workers will therefore arrive with varying convocation time [3]. To better estimate the reliability of the FLEX/MACST equipment in a probabilistic way, some researchers have applied HRA methods to the actions utilizing mobile equipment to gain important insights for the application guidelines [7]. Two of the important issues to address when using the ABM for simulating the on-site mobile equipment installation time distribution are 1) performance time for mobile equipment utilization from the time when the personnel arrive on site and 2) lack of staff due to environmental or accessibility issues affecting the performance time. Utilizing a method where Kim et al. proposed to estimate the staffing-level-based performance time [7], this study propose the rate of equipment installation to be used in the agents behavior model as shown in Equation 1, assuming linear rate of increase in time when the minimum staffing level perform the task compared to the regular number of workers (e.g. from safety drills).

$$R_{cs} = \begin{cases} 0, & N_{cs} < N_{ms} \\ \left[T_{rs}\left(1+\left(\frac{T_{ms}}{T_{rs}}-1\right)\cdot\left(\frac{N_{rs}-N_{cs}}{N_{rs}-N_{ms}}\right)\right)\right]^{-1}, & N_{ms} \le N_{cs} < N_{rs} \\ T_{rs}^{-1}, & N_{cs} \ge N_{rs} \end{cases} \quad \text{(Eqn. 1)}$$

where the subscripts *cs*, *ms*, and *rs* stands for current staffing level, minimum staffing level, and require staffing level. R is the rate of installation [time unit^{-1}], N is the number of personnel/off-site convocated workers, and T is the time required to complete the task (i.e. installation).

The installation status value (*ISV*) of the mobile equipment will range from 0 to 1 after the equipment arrives at the required reactor unit. Then, after each time step, the above R_{cs} may be multiplied to Δt and be added to the previous installation status value, as shown in Equation 2.

$$ISV^{(t)} = ISV^{(t-1)} + R_{cs}^{(t)}\Delta t \quad \text{(Eqn. 2)}$$

During the installation, if more workers come, the R_{cs} may change and thus simulated speed of how fast the mobile equipment is installed will change. In other words, the installation rate (and thus the time expected to install the mobile equipment) will change as more workers arrive to the target equipment. The above behavior rules will be modeled into the equipment's behavioral rule in the MCABM.

If the number of workers available for installing the specific mobile equipment is insufficient, then the failure probability of that task would be 1. However, it is more than likely that the installation of the mobile equipment will take place with even the limited number of workers arriving at the SC (safety center) where the most mobile equipment are stationed. Instead of assuming 6 hours of no help from the off-site convocated workers, this would allow more realistic assessment of the multi-unit accident management using the mobile equipment.

4. Future Work

For the future work, the time it takes to install the specific mobile equipment (such as 1MW mobile generator and portable low pressure pumps) will be estimated using the similar approach. Then, the convocation time distributions of the emergency organizations and off-site convocated workers simulated using Monte-Carlo Agent-Based Model (MCABM) approach from reference [3] can be combined with the results from the method proposed in this study. Once these two results (convocation time from off-site and installation time for on-site) are combined to find the overall time distributions, the results can be used as important information for the multi-unit HRA (Human Reliability Analysis) and to ultimately be used in MUPSA for assessing more realistic risk-reduction impact from the multi-unit accident mitigation using mobile FLEX/MACST equipment.

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