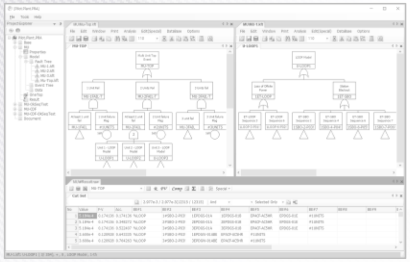
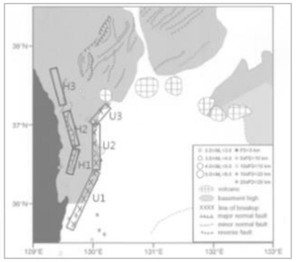
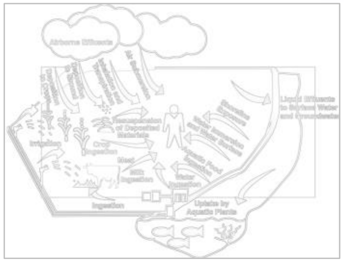
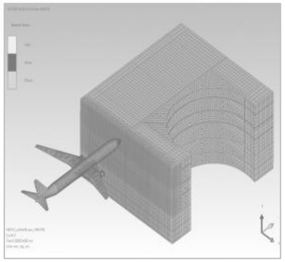

Proposal to Estimate the Mobile Equipment Installation Time during a Multi-unit Accident Management using an Agent-Based Model

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Presentation for 2024 KNS Spring Meeting Session 6B

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CONTENTS

1. Importance of Multi-Unit PSA

- **The Fukushima Daiichi accident showed that extreme external events beyond design-basis could occur with NPPs**
- **If there are multiple units on a single site, traditional single-unit PSA may not be enough to realistically assess the actual risk of the NPPs**
- **To account for inter-organizational interactions and inter-unit dependencies, multi-unit PSA should be performed to provide better insights**

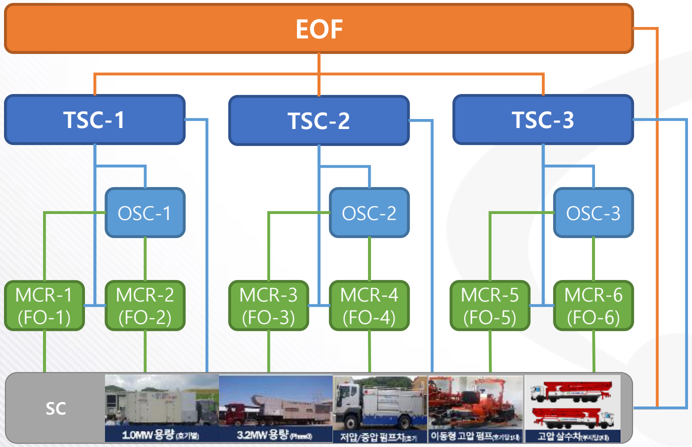
Multi-unit Accident in Fukushima

Concept of Multi-Unit Accident Mitigation and MACST (Multi-barrier Accident STrategies)

1. Importance of Multi-Unit HRA

- When a multi-unit accident occurs, MCR must make calls for off-site convocation of appropriate EROs (emergency response organizations
- During the Fukushima accident, human and organizational errors (convocation, communication, diagnosis, execution, etc.) were part of the factors that worsened the accident situation
- When developing MUPSA models, human failures with inter-unit dependencies need to be considered (i.e. MUHRA)

An example of organizational structure for emergency response during multi-unit accident in a six-unit site



General Process of an HRA
1. (Accident) scenario analysis
2. Identification and definition of human failure events (HFEs)
3. Feasibility analysis of HFEs
4. Detailed task analysis of HFEs
5. Quantification of human error probabilities (HEPs) for HFEs
6. Integration of HEP values into PSA

1. Importance of Time Distribution Estimations

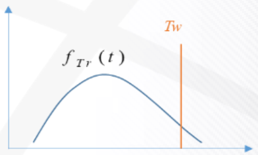
- **In the multi-unit accident, workers may be shared among different units for transferring, installing, refueling, and performing maintenance of the mobile equipment**

- **To quantify HEPs (human error probabilities) of the shared equipment failures, values for the mobile equipment installation times may be used**
  - Time required vs time available (lognormal):
  - Proposed method for MACST HEP:

$$P_{time} = 1 - \Phi\{\ln(T_w - T_r)\,/\sigma\}$$

T_w = Time available

T_r = Time required



$$HEP_{MACST} = P_{comm} + P_{dec} + P_{exe} + P_{time}$$

P_{comm} = coordination and communication failure

P_{dec} = decision-making errors related to organizational factors, procedures, and situation awareness

P_{exe} = execution errors in delivering, connecting, and operating equipment

P_{time} = insufficient performance time (time required to complete the goals) considering convocation, operation, and decision making

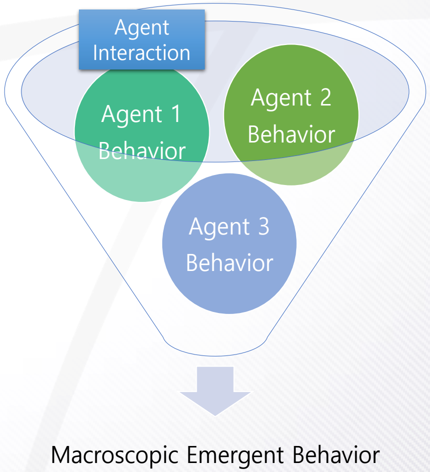
- **Since it is not possible to experiment an extreme event, a simulation model may be developed as an alternative**

1. Research Purpose and Objective

- **Purpose:**
  - To improve site-level safety of the existing NPPs through insights from the MUPSA and MUHRA
- **Objective:**
  - To estimate the time reference values and distributions mobile equipment installation time during extreme events
    - Ultimately to be used in the HEP quantification for MUPSA modeling purposes

2. Agent-Based Modeling (ABM)

- **Programmed functionality of autonomous agents to see the events emerge from individual perspective**
  - Modeling what actions an agent will take based on defined variables and functions
  - Agents adhere to its own behavioral rules, function independently, and interact as distinct parts of simulation
- **Analyzing macroscopic pattern through individual objects, their behaviors, and their interactions through bottom-up approach**
  - Micro-specifications generate macro-structure



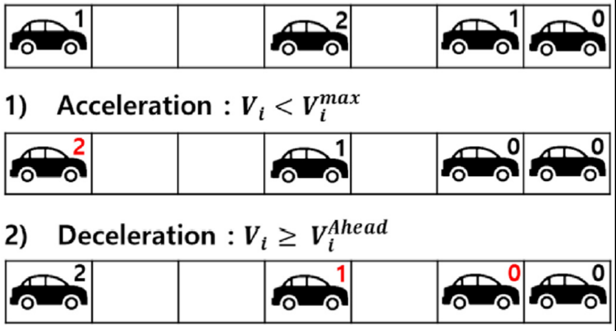
2. Two Parts of ABM: Off-site and On-site

- **To estimate the mobile equipment installation time during a multi-unit accident management, we propose to link two parts of different ABM simulation**
  - Off-site: off-site workers convocation time distribution to arrive to the plant site
    - PRISM-EC developed in Kyung Hee University modified for off-site workers convocation time estimation

$\boldsymbol{Optim}$: Optimal path nodes $(k \times 1)$ $1 \le k \le n$
$\boldsymbol{O}$: Open nodes, which have not been explored yet $(m \times 1)$ $1 \le m \le n$
$\boldsymbol{F}$: Vector of all nodes $(n \times 1)$
$mynode$: Current node (variable)
$lastnode$: End node, destination (constant)
$neighbornode$: Nodes connected with $mynode$, $neighbornode \in$
$nextnode$: Next path node, $nextnode \in neighbornode$
n : Number of all nodes
m : Number of nodes that can be explored
k : Number of explored optimal path nodes
i : Row, node number $1 \le i \le n$
j : Column, node number $1 \le j \le n$
g : Cumulative distance
$\mathbb{V}_{i,j}$: Distance between nodes $(n \times n)$

```
Initialize
  O = F
  mynode = 1
  Optim_1 = O_mynode
  g = 0
For i = 2 to k
  If (i = neighbornode and O_i is unavailable)
  O = O − O_i
  Else If (i = neighbornode and O_i is available)
        nextnode = { argmin_{j∈all available neighbornode} { V_{mynode,j} } }
        g = g + |V_{mynode,nextnode}|
        Optim += O_nextnode   ; size 1 increase
        O = O − O_nextnode
        mynode = nextnode
        If (mynode == lastnode)
              Break
        End If
  End If
Next
```

A* algorithm path optimal selection model pseudocode

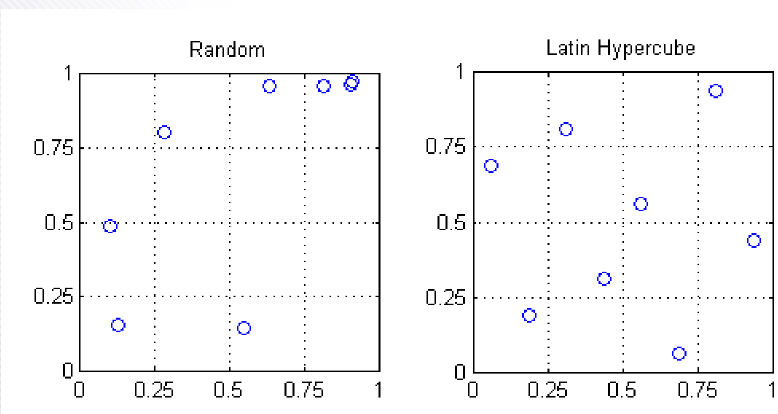


Nagel-Schreckenberg cellular automata model

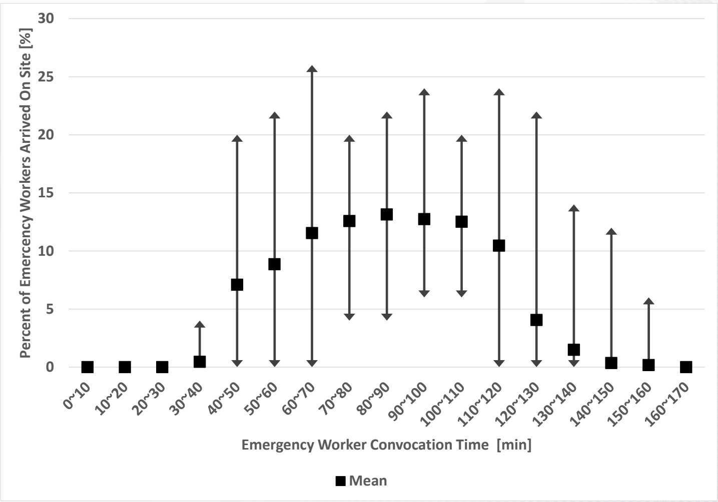
  - On-site: preparation, transportation, installation (connection, alignment)

2. Using Monte Carlo

- **Latin hypercube sampling (per each simulation) and simple random sampling (per agent) to (at least partially) account for uncertainties of the factors shown later**
  - Speed multipliers and starting time for each worker used information from Hokkaido university's research
    - S. Jang, et al. Consideration of key factors for estimating convocation time of emergency response crews under seismic event occurrence through Japanese case study, Transactions of the Korean Nuclear Society Autumn Meeting, 2023



Example of comparing eight samples from two Monte Carlo methods (for two parameters with uniform distribution)



Example of simulated off-site convocation time distribution results from previous work

2. Starting from Off-site ABM (Convocation)

- **For estimating convocation time of the off-site emergency response workers, preparation time and movement time are considered**
  - Regarding preparation, the workers would assess the situation, prepare for departure, and confirm safety of the close family members before actually departing to the plant site
  - Regarding movement, decrease in speed from road conditions from external events are considered
- **Three different cases of extreme events were modeled and simulated**
  - Weak event: where cars can be driven as normal (up to 1.6x the speed limit)
  - Medium event: where there is additional 50~80% decrease in movement speed (based on previous studies from Hokkaido University)
  - Strong event: where everyone needs to walk within 10km from the plant site

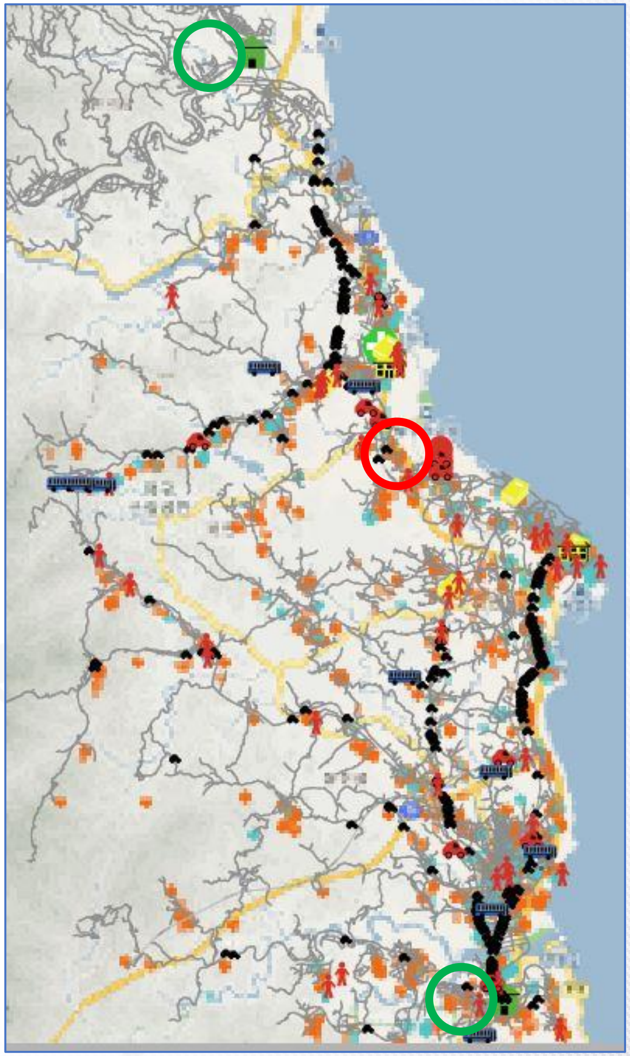
2. Starting from Off-site ABM (Convocation)

- **Simulation assumptions:**
  - No environmental release of radiation
  - Preparation time for the workers may range from 20 min to 100 min (Hokkaido University study)
  - From the aftereffects of the earthquake, 2.9~7.8% of the convocation workers may not be able to respond to the convocation call (Hokkaido University study)
  - For each simulation set, there is one-thirds chance of being either a day, afternoon, or night
    - During the days, afternoons, and nights, it is assumed that the maximum speed of the cars gets multiplied by factors of 0.8, 0.7, and 1.2, respectively
  - All convocation workers are living in random areas ~10km away from the study case plant site (map data converted from QGIS in PRISM-EC)

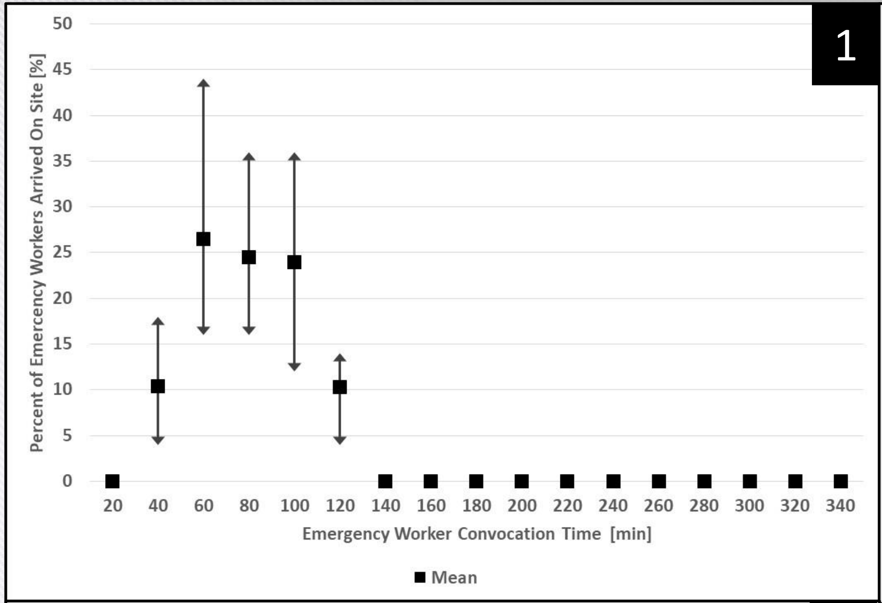
Parameters	Value
Number of Simulations per Case	25
Time Step	10 sec
Number of Convocation Workers	100
Number of Evacuees	300
Convocation Preparation Time	20~100 min (uniform distribution)
Determination of the Final Convocation Worker Arrival	92.2~97.1% (uniform distribution)
Time of the Day	Day, Afternoon, Night (uniform distribution)
Method of Movement	Car / walk
Nominal Vehicle Speed Limits	30 / 50 km/h
[Weak Event] Speed Increase from Speeding	0-60% (uniform distribution)
[Medium Event] Speed Decrease from Road Damage	50-80% (uniform distribution)
[Strong Event] Walking Speed	3.6-5.76 km/h (uniform distribution)

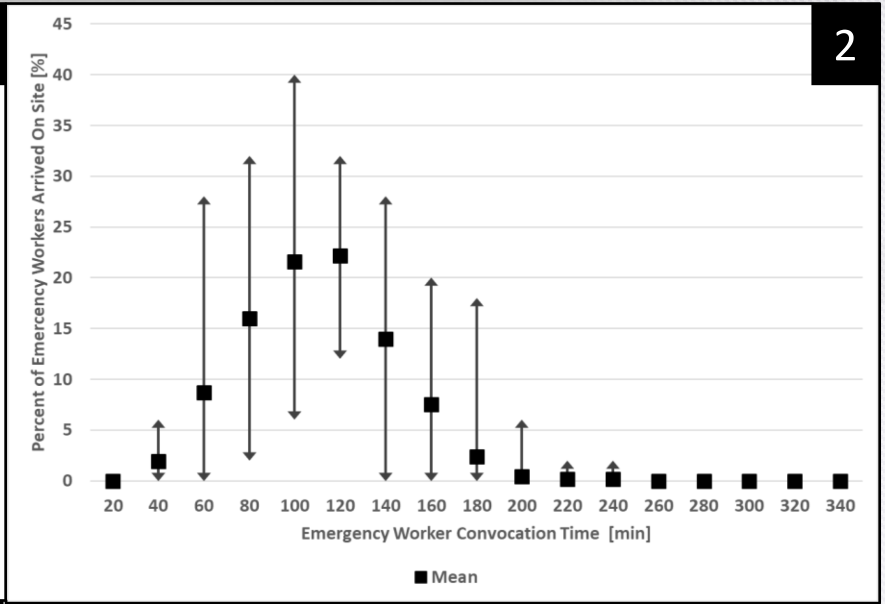
3. Off-site ABM Results (Convocation)

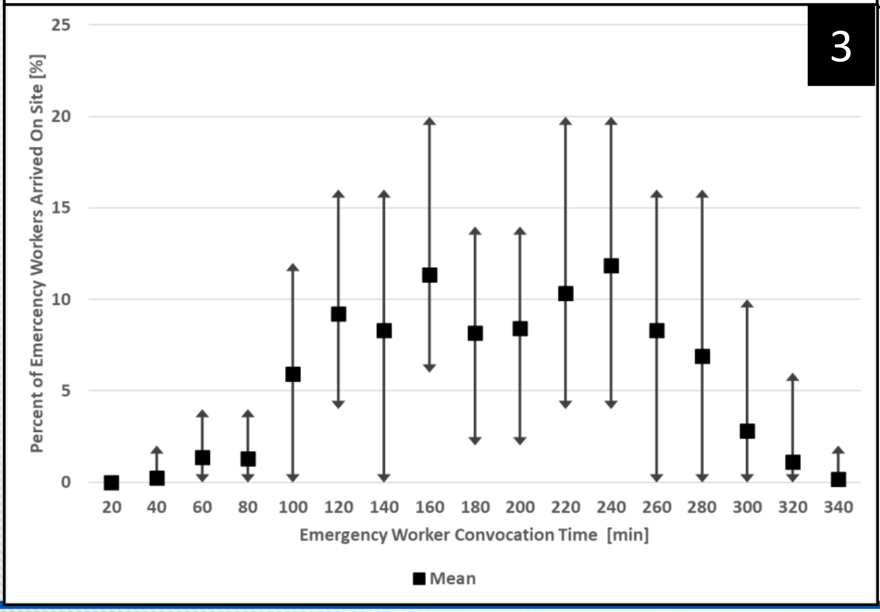
- **Simulation screenshot**



3. Off-site ABM Results (Convocation)







Simulated off-site worker convocation time distributions for 1) weak, 2) medium, and 3) strong external events

3. Off-site ABM Results (Convocation)

Simulated off-site worker convocation arrival percentile reference times for 1) weak, 2) medium, and 3) strong external events in minutes

Percent Arrival		25%	50%	75%	Finished
Weak Scenario	Min	44	60	80	103
	Max	63	80	96	116
	Mean	52	70	91	108
Medium Scenario	Min	56	81	98	120
	Max	114	142	174	229
	Mean	82	103	126	153
Strong Scenario	Min	117	150	214	259
	Max	165	215	267	324
	Mean	139	188	238	294

Probability that target percent will arrive by walk by the selected time limit (strong event)

Convocation Target Percent	1h	2h	3h	4h	5h
20	0	28	100	100	100
30	0	0	100	100	100
40	0	0	72	100	100
50	0	0	24	100	100
60	0	0	0	100	100
70	0	0	0	80	100
80	0	0	0	16	100
90	0	0	0	0	100

3. Off-site ABM Insight & Limitations

- **Need to consider the convocation of the off-site workers without using cars (i.e. by walking) for the multi-unit accident management procedures & guidelines**
- **Need to consider spontaneous arrival of off-site workers**
- **Difficulties in quantifying various sources of behavior uncertainties**
- **Difficulties for validation**

4. On-site ABM (Installation)

- **Unlike during safety drills in the NPP sites, off-site workers will arrive with varying convocation time**
- **Two of the important issues to address when using the ABM for simulating the on-site mobile equipment installation time distribution are:**
  - Lack of staff due to environmental or accessibility issues affecting the performance time (link with off-site ABM convocation time model)
  - Performance time for mobile equipment utilization from the time when the personnel arrive on site (ongoing work)

4. On-site ABM (Installation)

- **Proposed equipment installation rate based on staffing level**

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

Variables

R: the rate of installation [time unit^{-1}]
N: the number of personnel/off-site convocated workers
T: the time required to complete the task

Subscripts

rs: recommended staffing level for the task (e.g. during training)
ms: minimum staffing level for the task
cs: current staffing level

- **Proposed installation status value (ISV) at timestep t**
  - ISV starts from zero and reaches up to 1, at which the task becomes completed

$$ISV^{(t)} = \min\left(ISV^{(t-1)} + R_{cs}^{(t)} \Delta t, 1\right)$$

4. Discussions

- **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**
- **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**
- **For the future work, the time it takes to install the specific mobile equipment (such as 1MW mobile generator) will be estimated using the proposed methodology**
    - Difficulties in defining values for “minimum” staffing level and time for the task

THANK YOU