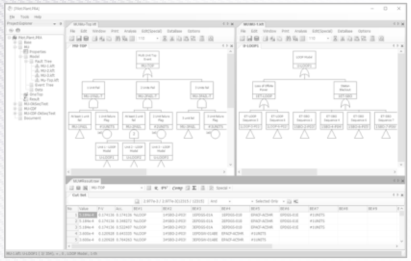

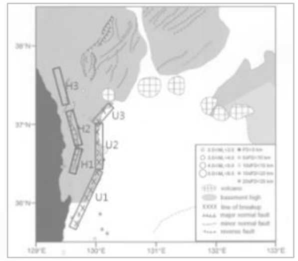

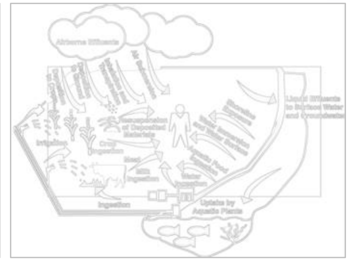

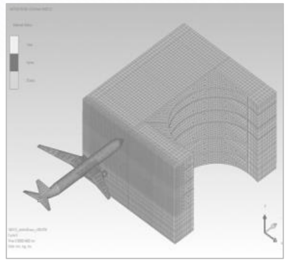

Proposed Methodology to Estimate the Off-site Emergency Response Convocation Time during Multi-unit Accident Management using an Agent-Based Model

- Presentation for 2023 KNS Autumn Meeting -

2023. 10. 26.

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CONTENTS

1. Multi-Unit Accidents Analysis

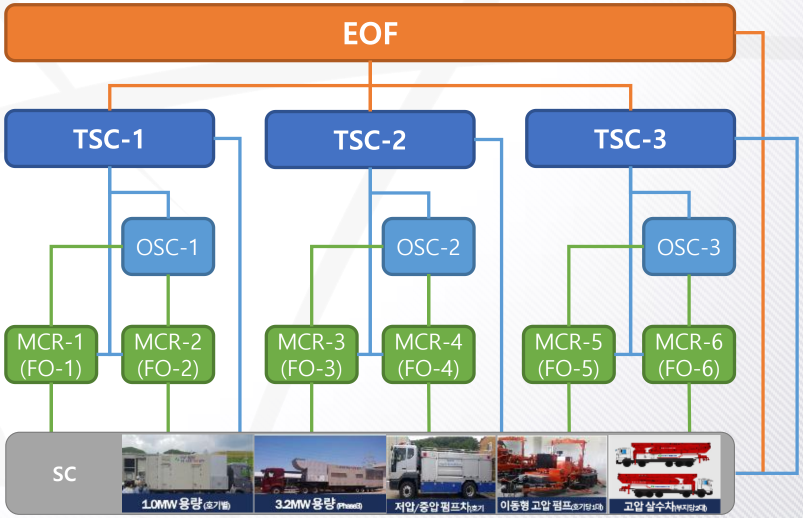
- **The Fukushima Daiichi accident showed that extreme external events beyond design-basis could occur with existing NPPs (nuclear power plants), even if such an event seems highly unlikely to occur**
- **NPP inter-unit dependencies may inflict core damages to the multiple units if not properly managed**
  - Simultaneously occurring initiating events in multiple units, proximity of the units, shared resources among the units, common operation practices, etc.
- **With many inter-unit dependencies among different units on site (especially in Korea), it is not enough to perform just traditional single-unit PSA to assess the actual risk of the NPPs**
  - MUPSA (multi-unit PSA) should be performed to provide insights and identifying critical contributors to the NPP site risk
  - Mitigative measures should be re-evaluated and improved at a site-level

1. Emergency Response Organizations

- **With an occurrence of multi-unit accident, MCR (main control room) operators of each NPP unit will declare an emergency based on the situation by following the site emergency plan**

- **One of very first responses the MCR must make is to call for convocation of appropriate EROs (emergency response organizations) from outside the plant site**
  - EOF (emergency operations facility), TSC (technical support center), OSC (operational support center)

- **In the AMP (Accident Management Program) and REP (Radiological Emergency Plan), aforementioned EROs will be launched after declaring radiological emergency within 1 hour and be functional within 2 hours**



An example of organizational structure for radiological emergency response during multi-unit accident for 6-unit plant site

1. Consideration of Human Factors

- **When developing MUPSA models, it is very important to consider human failure with inter-unit dependencies**
  - Example: shared workers for transferring, installing, refueling, and performing maintenance for portable equipment (e.g. MACST, Multiple Barrier Accident Coping Strategy)
- **To quantify HEPs (human error probabilities) for failure events of these portable equipment during multi-unit accident mitigation, representative values for the convocation time of the workers should first be known**
  - Outside workers not arriving in time may result in lack of staff for multi-unit accident mitigative measures, which may cause failure or delays in those measures
  - Ultimately, the time distribution of external workers arriving, transferring, and installing MACST may be used to quantify HEPs
- **Since the convocation times for extreme events cannot be experimented, a simulation model is being developed based on ABM (agent-based model)**

1. Purpose and Objective

- **Purpose:**
  - To improve site-level safety of the existing NPPs through insights from the MUPSA
- **Objective:**
  - To find reference values and distributions for convocation times during extreme events
    - Through simulation using an agent-based model
    - To be ultimately used for HEP quantification of multi-unit mitigative measures

2. Agent-Based Modeling

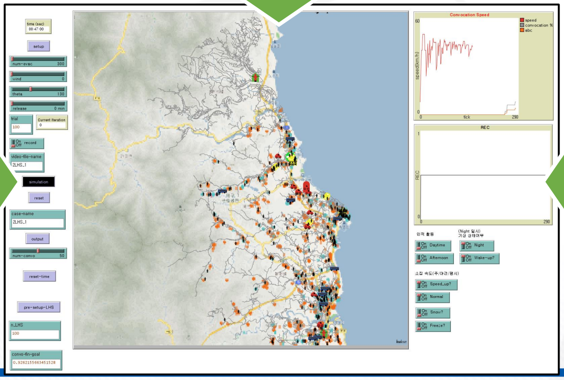
- **Programmed functionality of autonomous agents to see the events emerge from individual perspective**
  - Modeling what actions an agent will take based on defined variables and functions
  - Agents adhere to its own behavioral rules
  - Agents function independently and flexibly
  - Agents interact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

2. PRISM-EC

- **Developed in Kyung Hee University (Prof. Gyunyoung Heo) based on NetLogo Language**
  - Integrated development environment (IDE) for agent-based modeling
  - Refugees and workers are the agents
- **Ultimate goal is to simulate distributions and representative values for convocation time of the workers outside the plant**

Factors from external conditions (such as weather, time of the day, road conditions, etc.)

Factors affecting convocation workers preparation time



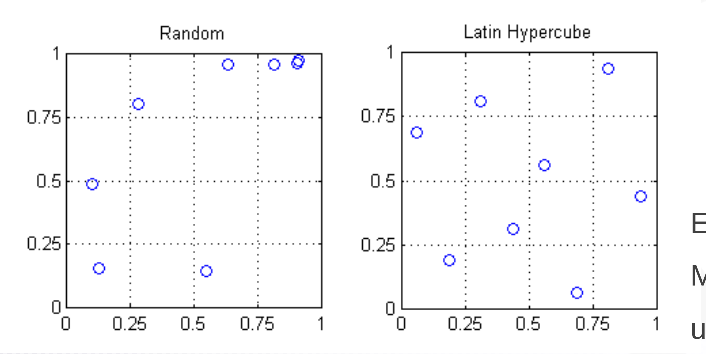
Factors affecting convocation workers movement time

2. Modeling and Uncertainty

- **Disclaimer: a model is not perfect**
  - Attempt to represent a system in a form to be used as an explanatory tool
  - Any model is at best an approximation (impossible to capture all the subtleties of the system behavior)
- **Two widely accepted ways to divide categories of uncertainties**
  - Parametric and modeling uncertainties
    - Parametric results from uncertainty in the quantification of a model with a specified functional form
    - Modeling results from appropriateness of the structure or mathematical form of the model
  - Stochastic (aleatory) and subjective (epistemic) uncertainties
    - Stochastic results from the fact that the system under consideration can behave in many different ways
    - Subjective results from the fact that the existing state of knowledge with respect to the correctness of the assumptions used in an analysis

2. Latin Hypercube Sampling (LHS) Method

- **Monte Carlo method was developed to address the need for parametric/stochastic uncertainty assessment through simulating distributions**
  - Random Monte Carlo sampling
    - Very easy to use
    - Possible clustering of the samples for small number of sample
  - Latin hypercube sampling scheme to reduce number of computations
    - Range of each variable is divided into non-overlapping intervals on the basis of equal probability to make random sample within each interval
    - Ensures that the random sampling is representative of the real variability



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

2. Sample Size Determination

- **Sample sizes recommended for two-sided nonparametric tolerance limits are shown below, where *p* is probability and *q* is confidence level**
  - Sample size solution found from *Conover, W. Practical nonparametric statistics, 2nd ed. (Wiley, New York, 1980)*

q \ p	0.50	0.75	0.80	0.85	0.90	0.95	0.975	0.98	0.99
0.50	3	7	9	11	17	34	67	84	168
0.75	5	10	13	18	27	53	107	134	269
0.80	5	11	14	19	29	59	119	149	299
0.85	6	13	16	22	33	67	134	168	337
0.90	7	15	18	25	**38**	77	155	194	388
0.95	8	18	22	30	46	93	188	236	473
0.975	9	20	26	35	54	110	221	277	555
0.98	9	21	27	37	56	115	231	290	581
0.99	11	24	31	42	64	130	263	330	662
0.999	14	33	42	58	89	181	366	458	920

- **In the preliminary analysis, 40 samples were chosen for 90%/90% probability/confidence level**
  - In consideration of limited time for simulation

3. Estimating Off-site Convocation Time

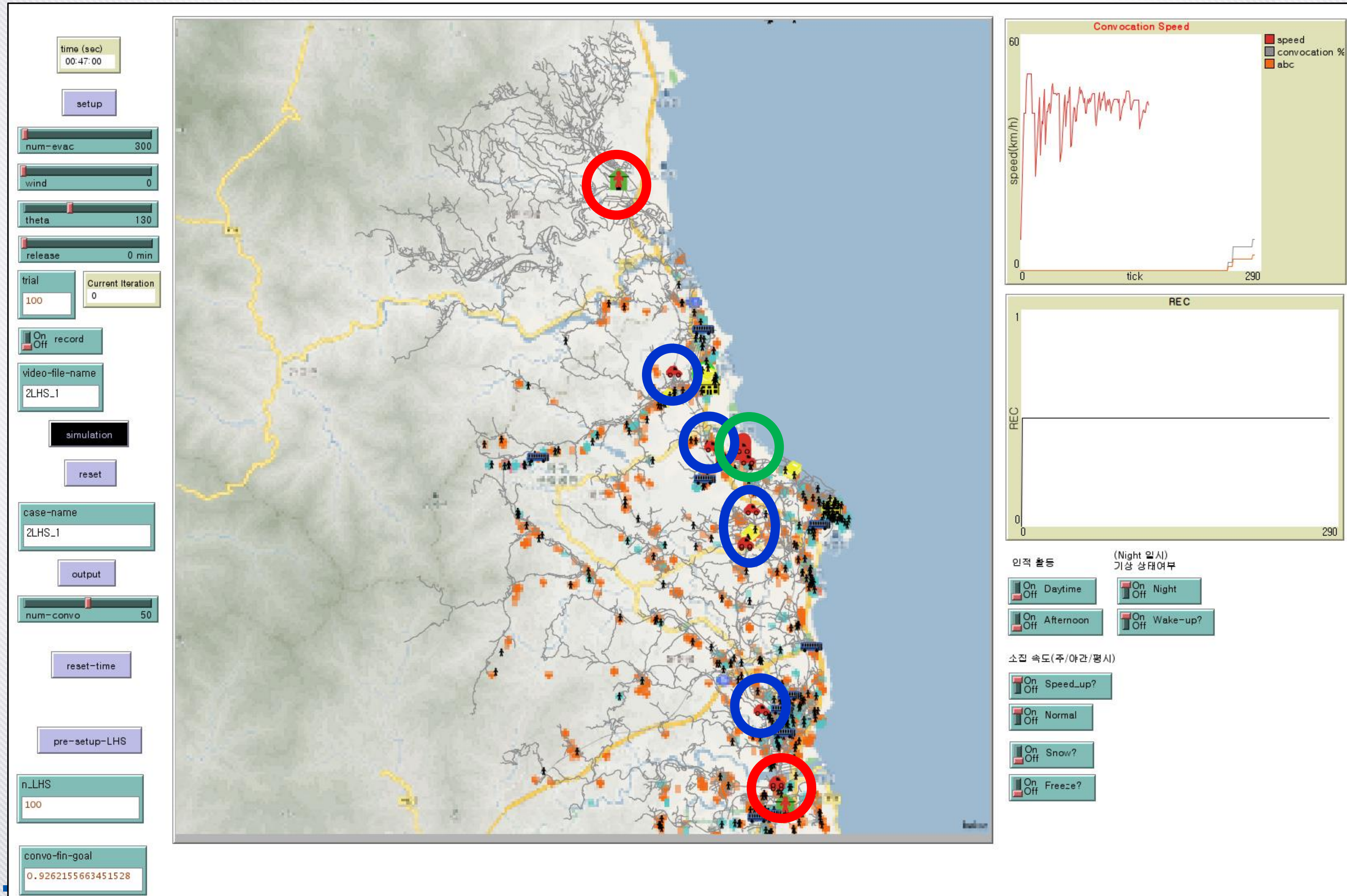
- **For estimating convocation time of the off-site emergency response workers, preparation time and movement time should both be considered**
  - Regarding preparation, the workers would assess the situation, prepare for departure, and confirm safety of the close family members before actually departing to the plant site
  - Regarding movement, decrease in speed from road conditions from external events should be considered
- **For some of the factors, results from Japanese case study by Prof. Jang of Hokudai is used (to be presented in same session at 11:20am)**
  - 2.9~7.8% of workers may not be able to meet the convocation call
  - About 50~80% decrease in movement speed during small-to-medium-sized damage
    - If large-sized damage on the road happens, impossible to have any types of transportation for a short term
  - Between 20~100 min for preliminary estimation of the preparation time

3. Case Study using PRISM-EC and LHS

- **External Event: Earthquake similar to 2011 Great Tohoku Earthquake**

- **Assumptions:**
  - No environmental release of radiation
  - Preparation time for the workers may range from 20 min to 100 min (Hokudai 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 (Hokudai study)
  - Assume small-to-medium-scale damage: 50~80% decrease in movement speed due to damages to the road and possible blackouts affecting traffic lights (Hokudai 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 stationed at housing provided by the nuclear company (not realistic, but only for case-study)

3. Screenshot of the Simulation



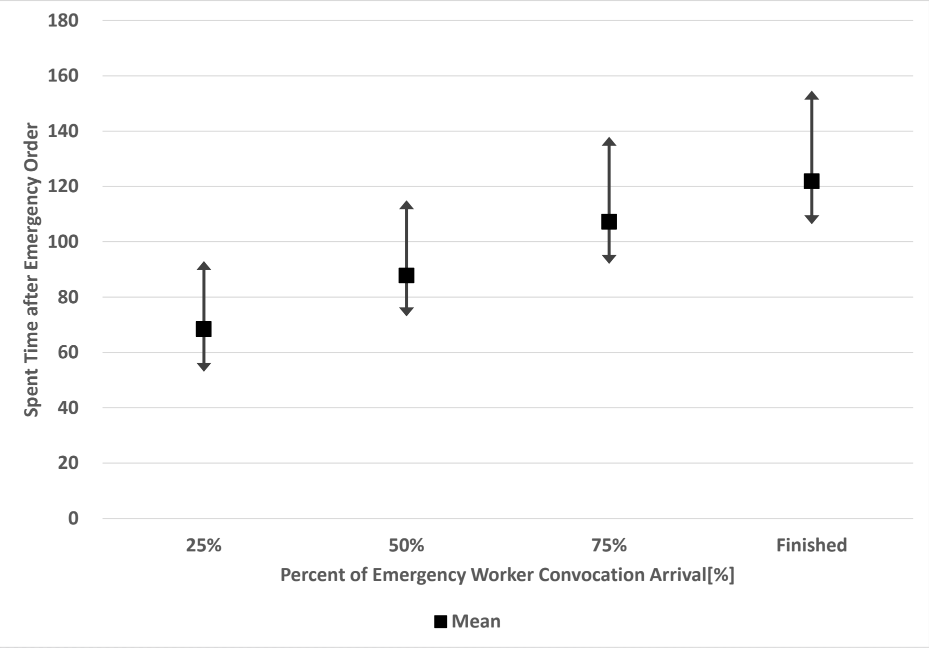
3. Case Study Parameters

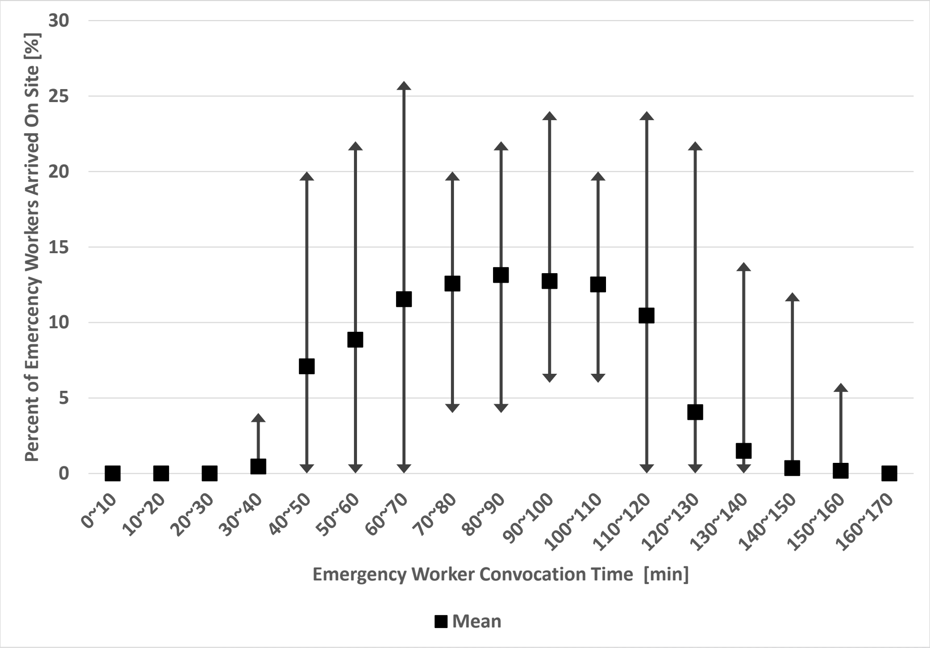
- **Below are some of the parameters used in the simulation of PRISM-EC and LHS**

Parameters	Value
Number of Simulations	40
Time Step	10 sec
Number of Convocation Workers	50
Preparation Time	20~100 min (uniform distribution)
Determination of the Final Convocation Worker Arrival	> 92.2~97.1% (uniform distribution)
Speed Decrease from Road Damage	50~80% (uniform distribution)
Time of the Day	Day, Afternoon, Night (uniform distribution)
Nominal Speed Limits	30 / 50 / 80 km/h

3. Case Study Results

- **From the case study, the convocations of external workers finished between 106~155 minutes, with an average of 122 minutes and standard deviation of 9.69 min**
- **50% of the workers from outside the plant arrived on site between 73~115 minutes, with an average of 88 minutes and standard deviation of 10.3 min**
- **Most of the workers arrived on site between 40~140 minutes after the convocation call**





4. Future Work

- **Much more work is expected for the improvement of the model/code**
  - Need to improve the model parameters (bases on choosing the values)
  - Include radiation release model
  - More variations in starting locations of the convocation personnel
  - Differentiate the personnel (EOF, TSC, OSC, KPS field workers, etc.)
    - Maybe model convocation workers moving on foot?
  - Code optimization (speed up)
- **Validation of the developed ABM model using reference site in Japan**
- **Simulating distributions and representative values for convocation time of the workers outside the plant for various cases of multi-unit accidents**
- **Developing time distribution models and finding representative values for the arrived workers to move to SC and transfer the necessary MACST equipment**
  - Last two bullets to be used in quantification of HEP for MACST activities in the MUPSA models

THANK YOU