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Risk- and Cost-Based Optimization of NPP System Multihazard Capacity using a Direct Cost Model

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1. Introduction

After the Tohoku earthquake-tsunami in Japan in 2011, securing the safety of the Nuclear power plant (NPP) against the multihazard became a critical issue to the nuclear society [1]. To ensure the safety of the NPPs from the multihazard threat, various efforts are made by both the regulatory bodies and the research community to reduce the multihazard risk. While enhancing the robustness of the NPPs against these single and multihazard, increasing the cost of the NPPs in safety measures brings an economic issue. In these circumstances, the NPP system capacity setting not only robust against the multihazard but also minimizes the monetary cost is required.

In the literature, a few attempts to optimize the NPP capacity aim to minimize risk and cost values [2-3]. In the authors' previous work, the multihazard capacity of the NPP system, structure, and component (SSC) had been optimized through a multi-objective genetic algorithm that uses risk and cost measures as the objective functions. Due to the lack of a cost model, this work adopts the indirect cost model, which assumes the linear relationship between the median capacity and the cost. In addition, the weighting factor is used to model the unknown ratio between the costs to bridge the cost due to two different hazards. Although such an indirect cost model provides a wide range of applicability due to its flexibility, further cost information is required for a realistic outcome.

Therefore, in this paper, to evaluate further practical optimized capacity settings for the NPP, authors utilize the further realistic cost model for both seismic and tsunami capacity in risk and cost-based NPP multihazard capacity optimization. Add to using direct cost models, further practical search boundary is also assigned. The rest of this paper is organized as follows. Section 2 introduces the seismic and tsunami capacity-cost model. Next, Section 3 presents the NPP system capacity optimization framework. Section 4, a numerical example of the proposed model, is illustrated, and Section 5 gives concluding remarks.

2. Multihazard Cost model for NPP SSCs

Collecting cost data corresponding to the hazard capacity is one of the most challenging aspects of risk and cost-based system capacity optimization. In this work, various non-linear models (e.g., step, quadratic functions) developed for the generic nuclear facilities (GNF) are adopted for the seismic capacity-cost modeling. As illustrated in Figure 1, the motor control center, Battery, and coolant pump are modeled in step function; the air handler, reactor vessel, steam generator, and core rod drive mechanism are expressed in the linear model; duct and piping are modeled in square root function, and lastly, the structure is represented in quadratic function. With these functions, various relationships between the seismic capacity and its corresponding cost are modeled in a realistic manner.

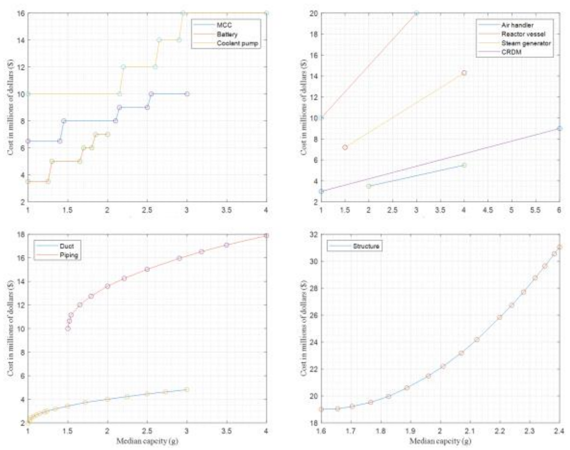

Fig. 1. Seismic capacity-cost model example of GNF in various functions

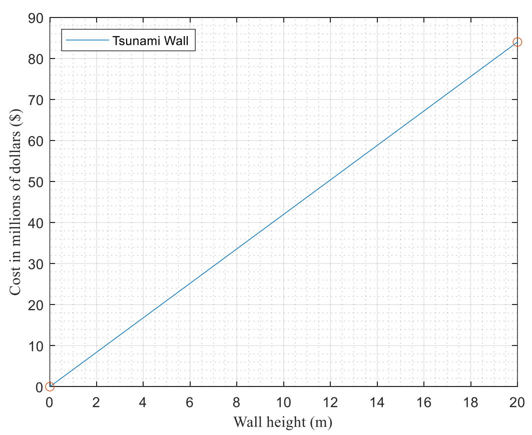

Fig. 2. Tsunami wall capacity-cost model (3km width)

The authors proposed the linear model for the tsunami capacity-cost model, which was developed based on the tsunami wall construction reports. After collecting various tsunami wall reports, the total cost of construction is divided into the height and width of the tsunami wall to evaluate the construction cost per unit (1m height, 1km width). While the construction cost can increase disproportionally to its height and weight, the linear assumption is applied in this model. The proposed model is illustrated in Figure 2.

3. Risk- and Cost-based NPP System Multihazard Capacity Optimization

3.1. NSGA-II

Since this work aims to identify the group of optimal NPP system capacity settings that can minimize both multihazard risk and cost, a multi-objective genetic algorithm (MOGA) is used. Especially, non-dominated sorting genetic algorithm II (NSGA-II), which is known for its efficiency in various applications (e.g., network [4], NPP system), is used for system optimization. As illustrated in Figure 3, NSGA-II uses non-dominated sorting and crowding distance sorting techniques to identify optimal samples in the sample space.

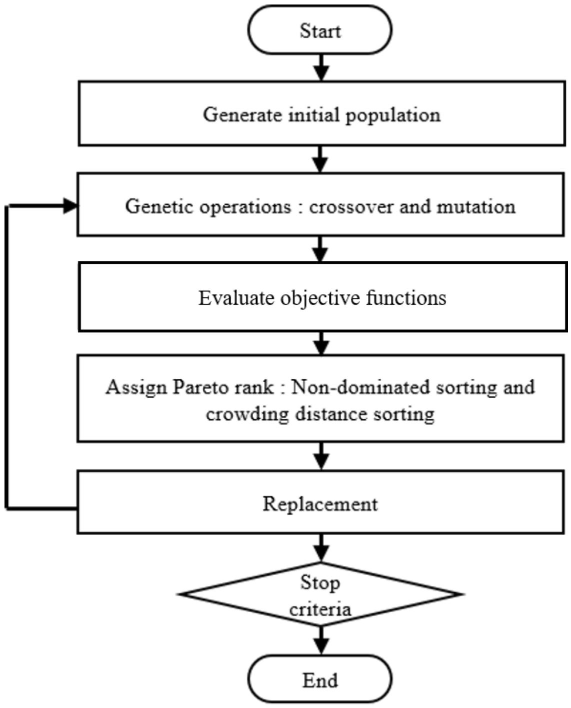

Fig. 3. Flowchart of NSGA-II

3.2. Objective functions

One objective function is to identify the sample that can minimize the multihazard (e.g., earthquake-tsunami) risk of the NPP system. Therefore, multihazard risk is evaluated. Two-stage direct quantification of the fault tree using the Monte Carlo simulation (Two-stage DQFM) method [5], which the authors previously developed, is employed for the multihazard risk assessment.

As one of the DQFM-based methods, two-stage DQFM can consider the partial dependency between the NPP SSCs, which is caused by its spatial proximity and structural similarity. A unique feature of the two-stage DQFM that differs from the original DQFM method is assigning different numbers of samples on each multihazard intensity point. Inspired by the fact that the contribution of the multihazard intensity point on the final multihazard risk value varies, two-stage DQFM assigns a large number of samples on the hazard point that contributed to the final system risk and a relatively small number of samples to those that have negligible impact. With this approach, two-stage DQFM showed reliable accuracy and high computational efficiency among the sampling-based multihazard PSA tools.

The second objective function is the total cost of setting NPP in a given multihazard capacity. Since this work utilizes the cost model expressed in monetary units for each SSC and the tsunami wall, evaluating the total cost of NPP itself is relatively simple. A total cost for the NPP system can be simply achieved by summating each SSC's cost at a selected capacity setting.

4. Numerical Example

4.1. Problem setting

To illustrate risk- and cost-based system multihazard capacity optimization through MOGA with the direct cost model, the GNF system model is employed. The GNF model is selected since it has a direct seismic capacity-cost model for SSCs in GNF, which is archived in the literature. The proposed approach can be applied to any system model with the direct cost model, yet to the best of our knowledge, it is difficult to find such a collection other than the GNF model. The fault tree model of GNF is illustrated in Figure 4.

The seismic fragility information [2] and tsunami fragility information [4], as well as a multihazard surface [3,5], are adopted from the literature. While constructing the tsunami fragility information, it is assumed that only three components (i.e., MCC, Battery, and structure) are exposed to the tsunami, and its median flooding capacity is assigned corresponding to the tsunami wall capacity.

In the case of NSGA-II, a population size of 100, a mutation ratio of 1/11, and a total of 250 generations were used. During the search for the optimal capacity, each NPP SCC capacity was sampled between the lower and upper bound of each cost model, as illustrated in Figure 1. The tsunami wall height was sampled between 5m and 20m.

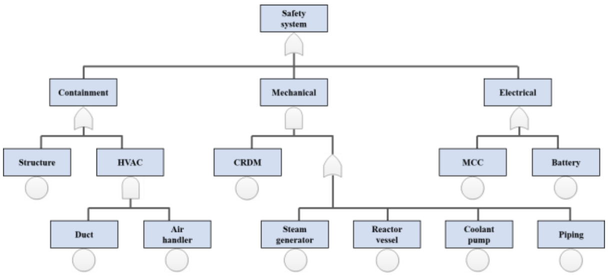

Fig. 4. Fault tree model of GNF (adopted from [2])

4.2. Results and Discussions

The Pareto surface of a group of optimal GNF system capacity sample sets is achieved using the proposed approach, as illustrated in Figure 5. Among various optimal sample sets, the system settings, which decrease cost by approximately 14.5% and reduce multihazard risk by 28.8% compared to the current GNF setting, are illustrated in Figures 6 and 7. Compared to the as-is capacity of GNF, it can be identified that optimal GNF setting assigns more monetary budget to tsunami wall while reducing the seismic capacity of overall SSCs.

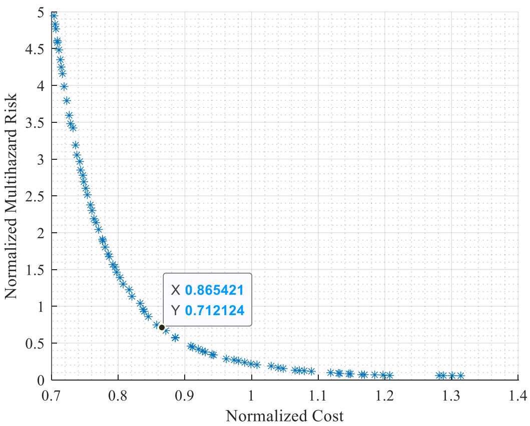

Fig. 5. Pareto surface of optimal GNF system in normalized cost and multihazard risk space

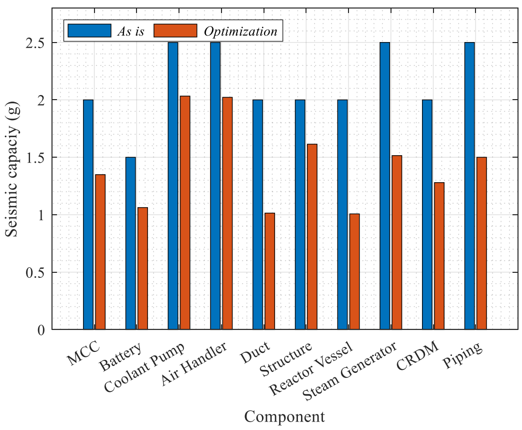

Fig. 6. Example of optimal seismic capacity setting

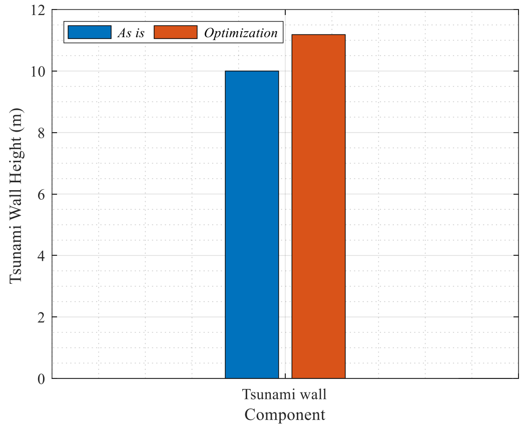

Fig. 7. Example of optimal tsunami capacity setting

5. Summary and Conclusions

In this study, a risk- and cost-based multihazard capacity optimization framework using a direct cost model is proposed. Based on the tsunami wall construction reports, a linear cost model proportional to its width and height is also proposed to model tsunami wall cost. Through the numerical example, the optimal SSCs multihazard capacity is successfully identified.

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REFERENCES

[1] Choi, E., Ha, J. G., Hahm, D., & Kim, M. K. (2021). A review of multihazard risk assessment: Progress, potential, and challenges in the application to nuclear power plants. *International Journal of Disaster Risk Reduction*, 53, 101933.

[2] Bolisetti, C., Coleman, J., Hoffman, W., & Whittaker, A. (2021). Cost-and risk-based seismic design optimization of nuclear power plant safety systems. Nuclear Technology, 207(11), 1687-1711.

[3] Choi, E., Kwag, S., & Hahm, D. (2024). Multihazard capacity optimization of an NPP using a multi-objective genetic algorithm and sampling-based PSA. Nuclear Engineering and Technology, 56(2), 644-654.

[4] Choi, E., & Song, J. (2020). Cost-effective retrofits of power grids based on critical cascading failure scenarios identified by multi-group non-dominated sorting genetic algorithm. International Journal of Disaster Risk Reduction, 49, 101640.

[5] Choi, E., Kwag, S., Ha, J. G., & Hahm, D. (2021). Development of a two-stage DQFM to improve efficiency of single-and multi-hazard risk quantification for nuclear facilities. Energies, 14(4), 1017.