Aalto University
MS-E2177: Seminar on Case Studies in Operations Research

Probabilistic Seismic Hazard Analysis for a Nuclear Power Plant

Interim Report

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1 Changes in project objectives and scope

The primary scope and objective, refining existing statistical models for estimating the maximum magnitudes of earthquakes in the context of Loviisa's PSHA, have remained unchanged. However, since the project's inception, Fortum requested an additional task of documenting the use of the Bayesian method [1] in Fortum's 2021 PSHA. This request was driven by the need for greater clarity and transparency, as the method had previously been implemented by an independent consulting company. We have since completed this task, and our findings are briefly discussed in the next section. Regarding Kijko's method [2], the objective and scope remain completely unchanged.

2 Project status

This section provides an overview of the project's status, detailing both completed and upcoming tasks for the two selected analysis methods.

2.1 Literature review

We have started to conduct a literature review that looks especially at other related projects and studies in PSHA. The aim is to conduct a thorough look at the existing pool of research to support the findings in our project. It is critical that the project results can be backed by existing research as this increases the validity of results, and Fortum can also stand more confidently behind the results.

2.2 Bayesian method

We categorized the tasks related to the Bayesian approach into three distinct groups, each with its own timeline and designated responsible persons.

2.2.1 Developing the Bayesian prior

Thus far, we have conducted an extensive literature review on the formulation of the prior in the Bayesian method. Drawing from the 1994 and 2016 EPRI studies [1, 3], we replicated the necessary computations to construct the prior and applied them to new subsets of the global earthquake catalog. In our initial approach, we utilized existing superdomains, which are geographical groupings based on variations in crustal tectonic features, to develop a more suitable prior for Loviisa using data exclusively from its corresponding superdomain. Our second approach, which employs differing clustering-based methods, is currently in progress and remains on schedule for completion.

2.2.2 Expanding data samples and updating the prior

The task of expanding the data sample through synthetic data simulation is in the literature review and implementation phase. It remains on schedule for completion. The Bayesian method consists of two parts: the first is the construction of the prior distribution, and the second is the construction of the posterior distribution by updating the prior with evidence. As the update is dependent on the existence of the prior distribution, this task is on literature review phase.

2.2.3 Bayesian method in Fortum's 2021 PSHA

The newly added task of evaluating the Bayesian method used in Fortum's previous PSHA is largely complete. The consulting company responsible for its implementation reports that they used a slightly modified version of a prior originally proposed in the 1994 EPRI study [1] without disclosing the specific nature of these modifications. With our current resources, we haven't been able identify all the modifications, although the results appear to align reasonably well with those reported in [1]. We will consult with our client to determine whether a more comprehensive evaluation of the report should be incorporated into our final deliverable or presented as a separate document.

2.3 Kijko's method

The maximum magnitude weights calculation using Kijko's method from Fortum 2018 report has been replicated. During replication and exploration, it is noted that the maximum magnitude weights are dependent upon the maximum observed earthquake magnitude, the minimum threshold magnitude chosen, and b value parameter in Gutenberg-Richter equation, as shown below.

$$\log_{10} N = a - bM \tag{1}$$

where

- N is the number of events having a magnitude $\geq M$.
- a and b are constants.

To update the weight values from Fortum's 2018 report, we use a new catalog published in 2021 by the University of Helsinki. The completeness analysis for this catalog was conducted in 2024 by Juhana Vehmas [4], assessing each seismic source zone (SSZ) in the Loviisa area. The SSZs are shown in Figure 1. Fortum's 2024 report then utilized this completeness-analyzed catalog to recalculate the b-values for each SSZ.

In our analysis, we will use the updated minimum threshold magnitude, maximum observed magnitude, and b-values to determine new maximum magnitude weights for the Loviisa region, with weights provided separately for each SSZ. When the weights for each SSZ are determined, a method for aggregating these values into a single set of weights is required. Currently, we plan to compute a weighted average of the SSZs within a 300 km radius of Loviisa. The weights may be determined based on the number of earthquakes in each SSZ. This method effectively represents each SSZ's contribution to the overall magnitude distribution by weighting zones based on their seismic activity, ensuring that more active zones have a greater influence on the final calculation. Alternative approaches that provide a stronger justification may still be considered. Further discussions with representatives from Fortum are necessary to evaluate the justifiability and relevance of the aggregating methods.

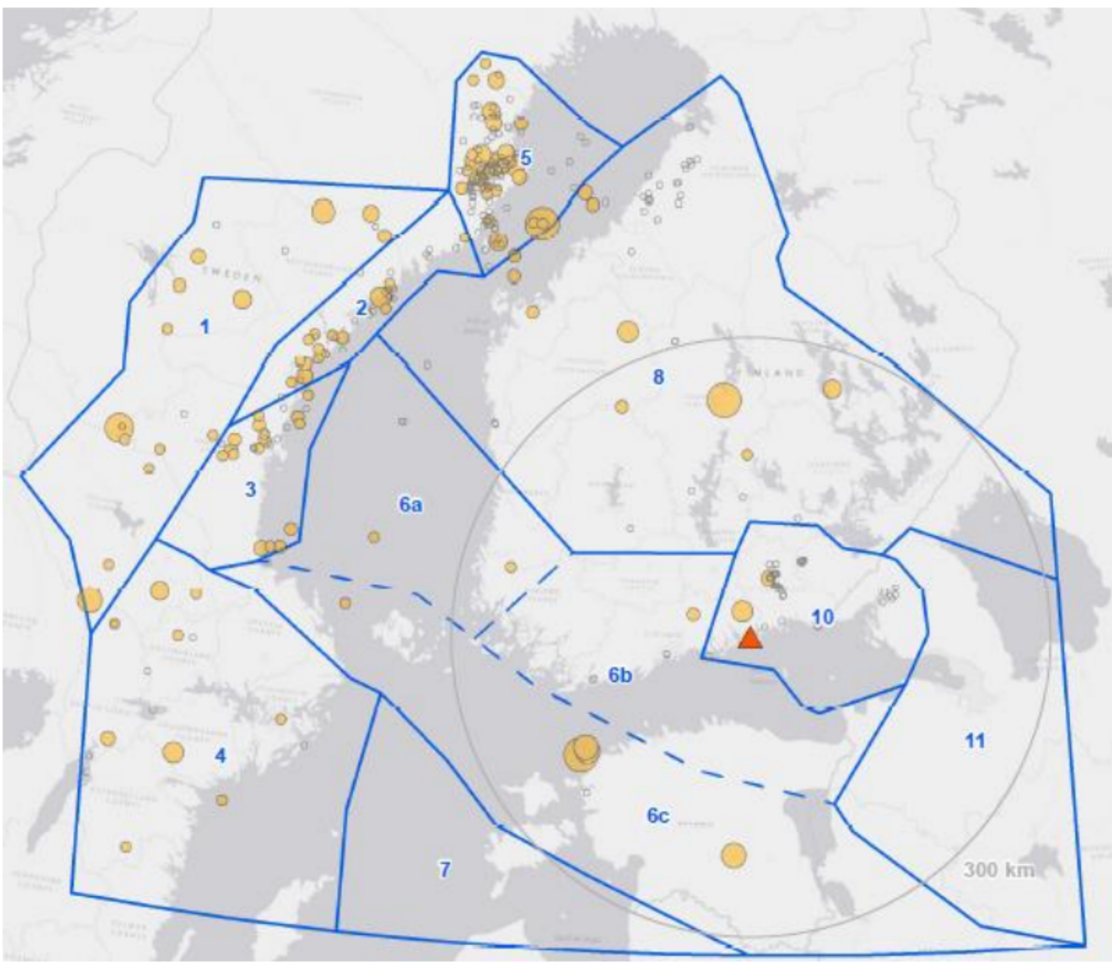

Figure 1: Seismic source zones (SSZ) and considered earthquake observations in Loviisa seismic hazard estimate 2021

3 Updated project schedule

The schedule for all tasks remains unchanged. In the Bayesian approach, the remaining steps involve completing the clustering task, selecting the prior, and updating it using either raw local data or a synthetically expanded data sample. For the Kijko method, as outlined in Section 2.3, the remaining tasks include calculating the maximum magnitude weights for each SSZ and determining an appropriate method for combining these weights.

Table 1: Project schedule.

Phase	**Start Date**	**End Date**	**Dependencies**	**Notes**
Task Division	01.02.2025	14.02.2025	None	Tasks assigned to team members
Finalizing Project Plan	07.02.2025	21.02.2025	Task division	Ensures clarity in execution
Literature Review & Initial Exploration	14.02.2025	31.03.2025	None	Background study on PSHA & statistical models
Model Implementation	01.03.2025	15.05.2025	Literature review, method selection completed	Implementation of Bayesian and Kijko's methods
Validation & Sensitivity Analysis	01.03.2025	10.05.2025	Model implementation	Ensures reliability of results
Final Report Documentation	14.02.2025	14.05.2025	Literature review, model implementation	Continuous process throughout the project
Presentation Preparation	06.05.2025	14.05.2025	Final report draft completed	Finalizing materials for course submission

4 Updated risk management plan

The risk management plan remains unchanged. While all identified risks are still present, none have materialized thus far.

Table 2: Main risks related to the success of the project.

Risk	**Effect**	**Likelihood**	**Impact**	**Prevention**
Insufficient validation and sensitivity analysis of the results	Results may not provide sufficient confidence for nuclear safety applications	Medium	High	Time block dedicated exclusively on validation and sensitivity analysis
Problem scoping too ambitious	Overworked team members, not staying on schedule	Medium	Medium	Emphasis on communication between team members and Fortum
Not enough relevant data available	Results not accurate / meaningful enough	Medium	Medium	Use all available data. Explore simulating methods and clustering of data.
Lack of communication with the client	Progress slowing down, project heading in an unwanted direction	Low	High	Biweekly meetups with Fortum representatives, confirmed a few days before meeting
Inactive team members due to unexpected life circumstances	Not staying on schedule, Overworked members	Low	Medium	Weekly / biweekly meetups, communication through Telegram, careful planning and monitoring

References

[1] A.C. Johnston, K.J. Coppersmith, L.R. Kanter, and C.A. Cornell. The Earthquakes of Stable Continental Regions: Assessment of Large Earthquake Potential. Technical report, Electric Power Research Institute (EPRI), Palo Alto, California, 1994.

[2] A. Kijko. Estimation of the maximum earthquake magnitude, m_{max}. *Pure and Applied Geophysics*, 161:1–27, 2004.

[3] K.J. Coppersmith, L.A. Salomone, C.W. Fuller, L.L. Glaser, K.L. Hanson, R.D. Hartleb, W.R. Lettis, S.C. Lindvall, S.M. McDuffie, R.K. McGuire, et al. Central and Eastern United States Seismic Source Characterization for Nuclear Facilities. Technical report, Electric Power Research Institute (EPRI), Palo Alto, California, 2012.

[4] J. Vehmas. Probabilistic Seismic Hazard Analysis for Nuclear Power Plant Sites in Finland. Master's thesis, Aalto University: School of Science, Espoo, Finland, 2024.