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Simulating the Evolution of North Korea's First Nuclear Test

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1. Introduction

North Korea has continuously developed its nuclear weapons program. In 2021, North Korea accelerated the advancement of its nuclear capabilities. Kim Jong-Un disclosed a massive military buildup plan to make the weapons "standardized, tactical and weaponized." [1] Also, North Korea has repeatedly conducted provocative missile launches. It has fired missiles eight times in January and February of 2022. These activities and others are heightening tensions on the Korean Peninsula.

Discussions on the denuclearization have stagnated for a few years. Nuclear talks have been deadlocked since the failure of the Hanoi summit in 2019. The international community has shifted its focus to the COVID-19 pandemic since 2020. Also, the US foreign policy has recently concentrated on the escalating US-China competition. In South Korea, the presidential election has been a bigger issue than the North Korean threat.

As North Korea is implementing its nuclear weapons program, it is necessary to reduce the uncertainty of future negotiations. A more evidence-based and concrete denuclearization roadmap would increase the possibility of resuming nuclear talks. Improving the predictability of North Korea's nuclear weapons program would help designing such a roadmap. In other words, evaluating various available options and likely scenarios can provide insights into the roadmap design.

Based on this background, our study is simulating the evolution of North Korea's nuclear weapons program in the past. We applied the concept underlying the nuclear weapons latency computational tool [2] to the case of the first nuclear test in North Korea. The simulation projected the duration of that nuclear test program. Then, we compared the simulated result with the actual historical period. It is expected that this study will be helpful in developing quantitative evidence that supports a roadmap design for the denuclearization of North Korea.

2. Methods

North Korea's nuclear weapons latency was modeled in a Petri net simulation. Referring to Sweeney's 2019 definition [2], we defined North Korea's nuclear weapons latency as the expected length of time from the initiation of North Korea's nuclear weapons program to its first nuclear test. The Petri net theory was used to design the possible pathways leading to the nuclear test, starting with uranium mining. The theory uses a simplified network to structure a complex system with the minimum number of components. The completed network was used to conduct deterministic and stochastic transient simulations.

2.1. Network building

Prior to the simulations, the Petri net depicting the process of the first nuclear test in North Korea was built (Fig. 1). Experts estimate that the test material was plutonium metal, with the designed yield of 4 kt [3]. In this study, for simplicity, we assumed the yield of the test to be 5 kt, which is equivalent to 4 kg of Pu metal [4]. In general, the network was structured to focus on the main facilities involved in the nuclear fuel cycle: Bakcheon and Pyongsan uranium milling plants, Yongbyon fuel fabrication facility, IRT-2000 experimental reactor, Yongbyon 5MWe reactor, Radiochemical Laboratory with the plutonium reprocessing facility, and Punggye-ri nuclear test site. Steps in the construction and operation of each facility were included in the flow chart. A few pauses in the process, for example, freezing measures by the Agreed Framework in 1994, were also reflected. Time duration information for each step was collected from various reliable open sources [5].

Two types of the Petri net were structured: deterministic timed Petri net and stochastic timed Petri net. For the former, a deterministic time delay was designated for each transition to the next step. For the latter, a probability distribution function was defined for each transition. The probability distribution function was set to be a uniform distribution from 50% to 150% of the time duration used in the deterministic timed Petri net [2].

2.2. Simulations

Then computer simulations were conducted using the Petri nets and the software TimeNet v.4.5. We operated the transient simulation function, which is used to predict what the state of the network will be as time passes [6]. Based on Sweeney's definition, the resultant nuclear latency computed with the deterministic timed Petri net was defined as the standard nuclear latency, while the result of the simulation with the stochastic timed Petri net was defined as the expected nuclear latency [2]. For both types of Petri net, the simulation starting point was January 1962, when North Korea began to construct the IRT-2000 reactor. The simulation time period was 60 years (until 2022) with 600 sampling points – 10 points per year. The maximum relative error was set to be 10% with a 95% confidence level.

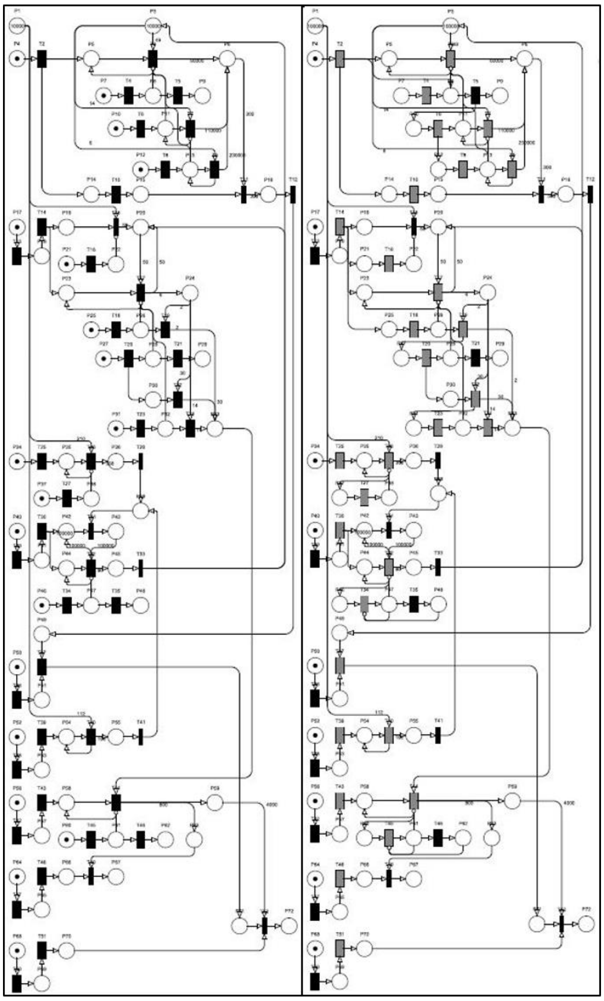

Fig. 1. The deterministic timed Petri net (left) and the stochastic timed Petri net (right) depicting the process of the first nuclear test in North Korea.

3. Results

Each simulation result included the transient state of the probability of conducting the first nuclear test in North Korea (Fig. 2a, Fig. 3a), the amount of plutonium produced from the IRT-2000 reactor (Fig. 2b, Fig. 3b) and from the Yongbyon 5MWe reactor (Fig. 2c, Fig. 3c), and the amount of plutonium extracted by the reprocessing process in the Radiochemical Laboratory (Fig. 2d, Fig. 3d).

3.1. Deterministic timed Petri net

Fig. 2 shows the results from the deterministic timed Petri net simulation. When the probability of the first nuclear test becomes 1, the time of the test would be was 43 years after 1962, which would be 2005. The plutonium produced from the IRT-2000 reactor increased linearly from 1968. The amount of plutonium produced from the Yongbyon 5MWe reactor increased from 1987 with a few downturns, which implied discharge of the used fuel. Correspondingly, plutonium separated in the Radiochemical Laboratory had jumped twice, once in 1990 and once in 2003. A small decrease occurred in 2004, indicating the use of 4 kg of plutonium for the nuclear test.

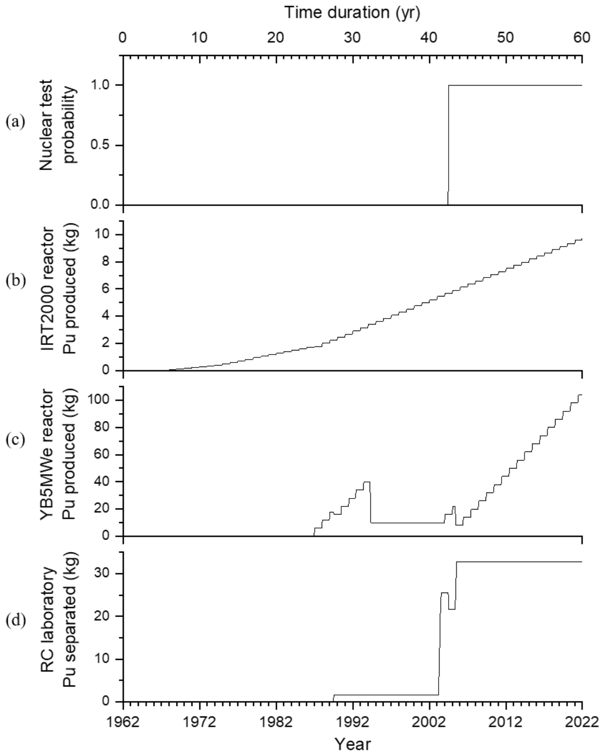

Fig. 2. Transient simulation result with the deterministic timed Petri net: (a) the probability of conducting the first nuclear test in North Korea (b) the amount of plutonium produced from the IRT-2000 reactor (c) the amount of plutonium produced from Yongbyon 5MWe reactor (d) the amount of plutonium extracted by the reprocessing process in the Radiochemical Laboratory.

3.2. Stochastic timed Petri net

The simulation results of the stochastic timed Petri net (Fig. 3) showed a similar trend to the deterministic case results. The average probability of the first nuclear test became nonzero in 2002, 40 years later after 1962, and then increased. It reached one after a decade (2012). The amount of plutonium in the IRT-2000 reactor began to monotonically increase in 1966. Plutonium production from the Yongbyon 5MWe reactor began in 1983. The amount of the material in the reactor had a local maximum and minimum in 1993 and 2003, respectively. The separated plutonium stockpile from the Radiochemical Laboratory rose from 1988.

4. Discussion

4.1. Standard nuclear latency

The standard nuclear latency can be obtained from the simulation with the deterministic timed Petri net. It is 43 years, since the probability of the first nuclear test became one from zero in 2005 when the deterministic timed Petri net was used (Fig. 2a).

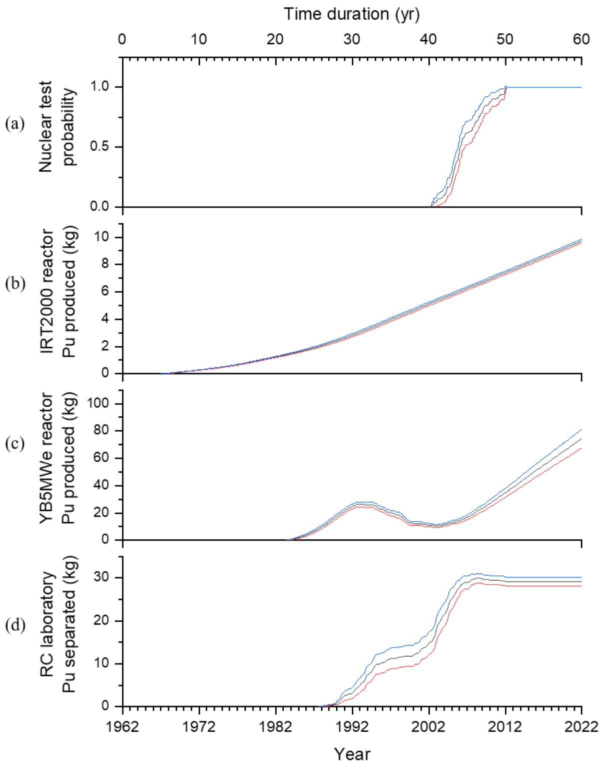

Fig. 3. Transient simulation result with the stochastic timed Petri net: (a) the probability of conducting the first nuclear test in North Korea (b) the amount of plutonium produced from the IRT-2000 reactor (c) the amount of plutonium produced from Yongbyon 5MWe reactor (d) the amount of plutonium extracted by the reprocessing process in the Radiochemical Laboratory. For each graph, black line is the average, while the red and blue lines indicate the minimum and maximum values, respectively.

4.2. Expected nuclear latency

Deriving the expected nuclear latency requires further calculations. The average probability of the first nuclear test illustrated in Fig. 3a means that there is no possibility that North Korea could conduct its first nuclear test before 2002, but it will have conducted the test after 2012.

Therefore, to estimate the time when the test most probably happened, the average of the probability distribution was computed. As indicated in Fig. 3a, the probability function was cumulative: the probability that the test has occurred between 1962 and the time point selected for analysis. Thus, the cumulative probability was divided into probability increments by sampling time units of 0.1 year. The result was a bell-shaped probability distribution (Fig. 4). The average of the probability distribution was 45 years after 1962, indicating a test in 2007. Hence, according to the stochastic timed Petri net simulation, the expected nuclear latency is 45 years because 2007 was the most probably expected time when North Korea would conduct the first nuclear test.

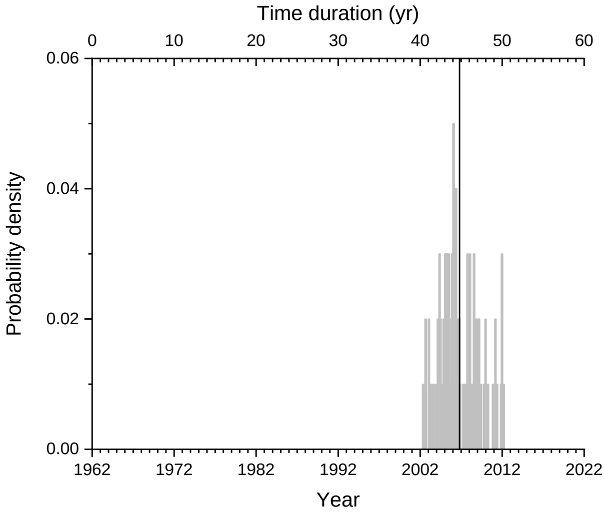

Fig. 4. Distribution (gray bars) and the average (black line) of the probability of the first nuclear test at each time point from the simulation with the stochastic timed-Petri net.

4.3. Simulation compared to the history

The simulation results fit well with the actual history and the known information. North Korea carried out its first nuclear test on October 9, 2006. Rounding up the date to 2007, the expected nuclear latency computed is the same as the historical point in time. The standard nuclear latency is also reasonably acceptable, considering that the simulation used fewer factors and less information on the nuclear program when compared to the actual events. In addition, it is known that the IRT-2000 reactor started operation in 1967, while the Yongbyon 5MWe reactor started operation in 1986 and discharged the used fuel after the shutdown in 1994. The date when the amount of plutonium production became nonzero in the stochastic timed Petri net simulation was only 1-3 years different than the actual date, which is reasonably acceptable.

5. Conclusion

We conducted a computer simulation-based experiment to simulate North Korea’s first nuclear test program by using Petri net theory. It showed that it could be possible to estimate how long it would take North Korea’s nuclear weapons program to achieve a nuclear weapons test. However, since North Korea has already completed six nuclear tests of different scales with different technologies so far, further Petri net simulations are required. A more sophisticated network design with more detailed data would enhance the certainty and credibility of this approach.

Such quantitative analyses are expected to support more realistic solutions to denuclearize North Korea. The lessons of the past five years indicate that an incremental phased-based denuclearization roadmap is more likely to succeed than striking a big deal. Using the approach suggested in this study, policy makers would be able to simulate a variety of North Korean nuclear weapons program scenarios to possibly identify the most efficient pathway to denuclearization. By simulating different options, we would be able to predict what might change in the future. The results would provide significant insights for ranking the priorities among all the available options on the table. Therefore, the improved predictability and certainty would support a more systemized and concrete roadmap toward the denuclearization of North Korea.

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