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Modeling the Multinationality and Other Socio-Political Aspects of the Nuclear Fuel Cycle

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1. Introduction

Nuclear fuel cycle is a complex process with numerous steps, which are influenced by both engineering and socio-economic factors. Therefore, as an interdisciplinary tool developed to study the dynamic complexity of a system, system dynamics has been used to simulate nuclear fuel cycle and to support the development of nuclear policies. A number of studies have been done in this area providing comprehensive view of nuclear fuel cycle in respect to the energy scenarios, material flows, and pricing mechanism. However, the effect of other socio-economic aspects like public acceptance, proliferation risks, or the trans-boundary nature of the nuclear fuel cycle have not been well illustrated by those previous researches. In order to inform decision makers of the suitability and sustainability of any nuclear fuel cycle option, a modeling tool has to adequately cover such issues. This paper is an attempt to develop such a hybrid model of multinational nuclear fuel cycle using system dynamics and the quantifiable effects of political and social impacts on the development of nuclear fuel cycle through multi-attribute analysis of historical data.

2. Methods and Results

Firstly, the conceptualization of the multinational and socio-economic characteristics of the nuclear fuel cycle is presented as the basis for the development of the system dynamics model. It is followed by the actual model with explanation on the formulization of the effect of different socio-political factors, and some exemplary results. Finally, the paper is concluded with some remarks on the significance of this model to nuclear fuel cycle modeling and nuclear policy this paper.

2.1 Conceptualization of a multinational nuclear fuel cycle

According to OECD/NEA, almost no nuclear power country in the world has a self-sustained nuclear industry and depends on the supply of uranium resources, and front-end or back-end services from other states (1). Moreover, there exists several aspiring countries like Vietnam, Jordan, or Bangladesh, which are preparing for their first nuclear power project without much expertise or technology. Due to the proliferation risks of some fuel cycle technologies like enrichment and nuclear reprocessing, the possession of these technologies are also restricted in a small group of countries while others are discouraged to acquire such sensitive technologies. Therefore, nuclear fuel cycle is inherently multinational and involves the trans-boundary movement of nuclear materials and services, thus the commercial and political relationships between participating states to such fuel cycle need to be considered in the simulation of any nuclear fuel cycle. Besides, the internal socio-economic conditions, especially the nonproliferation status, political and economic stability, and public acceptance of nuclear energy, have been proven important to the success of the nuclear power program (2).

Taking into account these socio-economic factors, a tripartite nuclear fuel cycle is conceptualized with three major players: “Country A” with uranium abundance operates the mining and milling industry that provides natural uranium for the whole process; “Country B” with fuel cycle capabilities converts, enriches, and fabricates natural uranium into nuclear fuel; “Country C” is the end-user of nuclear fuel for the operation of its nuclear power plants. This tripartite model in fact reflects the current situation of the nuclear industry, in which uranium is often mined from Australia, Canada or some African and Central Asian states before being processed at fuel cycle facilities in Russia or Western Europe and finally consumed in Asian states like China, the Republic of Korea, or Japan.

2.2 Modeling the socio-political effects of a multinational nuclear fuel cycle

Based on the tripartite causal-loop diagram presented above, the system dynamics model of a multinational nuclear fuel cycle was developed using Vensim (3). This model consists of a “uranium supplier”, a “service provider”, and an “end-user” and the transportation activities between them. The effect of the multinationality, or the political relation between these states, on the nuclear fuel cycle is thus represented by the delay time of transportation, according to which a worse bilateral relationship would delay the transportation of nuclear materials from one state to another.

The quantification of the socio-political effect on the nuclear cooperation between states has been examined by various researches (4). In line with these studies, our research examined the influence of the bilateral relationship on nuclear cooperation through the construction and quantitative analysis of a dataset on nuclear cooperation since 1990 (5). The correlation between bilateral cooperation among nations and the state of their political and economic relationships were assessed using linear and multinomial logistic regressions to identify the statistically significant correlations and their coefficients. Accordingly, the cooperation factor between states was quantified through Equation (1) as a linear combination of the socio-economic factors that are significant to the cooperation.

Pr(nuclear cooperation) = f(proliferation risk of end-user, uranium production difference, military relationship, military trade, geographical proximity, level of foreign investment, common enemy, nuclear public acceptance) (1)

Regarding the internal socio-economic aspect, the influence of nuclear public acceptance on the nuclear decision-making process was considered in this research. Accordingly, a lower level of nuclear public acceptance can induce delay of the construction process of new nuclear plants. The relationship between the level of nuclear public acceptance and various social and economic factors was examined by compiling and analyzing data on nuclear public acceptance worldwide from 1987 to 2014. Such relationship is represented here through Equation (2).

Pr(nuclear public acceptance) = f(education level, population density, geological quality, exposure to disaster, GDP per capita, military tendency, availability of renewable energy) (2)

2.3 Modeling scenario

As described in the previous Section, all three major players of the nuclear fuel cycle, namely the uranium supplier, the service provider, and the end-user, were considered for the multinational nuclear fuel cycle model. The results presented in this Section focuses on the end-user, which is in this modeling scenario a country of no significant uranium resources, with a medium-size nuclear power program, and supplied by a single fuel service provider. The development of the nuclear power program of this country is outlined in Figure 1.

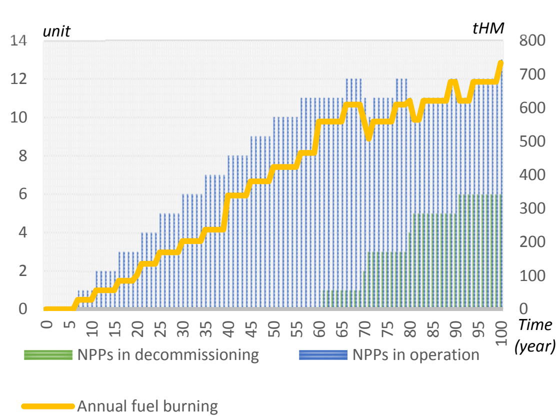

Fig. 1. Development of the nuclear power program with time (from year 0 to year 100) of the end-user country in the modeling scenario.

As the amount of spent nuclear fuel gradually increases with the development of the nuclear power program, the end-user country has three options for back-end fuel cycle management: Direct disposal (once-through cycle); separation of usable materials to return to the service provider (partly closed cycle); separation and reuse of usable materials (fully closed cycle). As spent fuel, reprocessed uranium (RepU), and separated plutonium have different level of weapon significant quantities (6), the proliferation risks of the three fuel cycle options are different as presented in Figure 2.

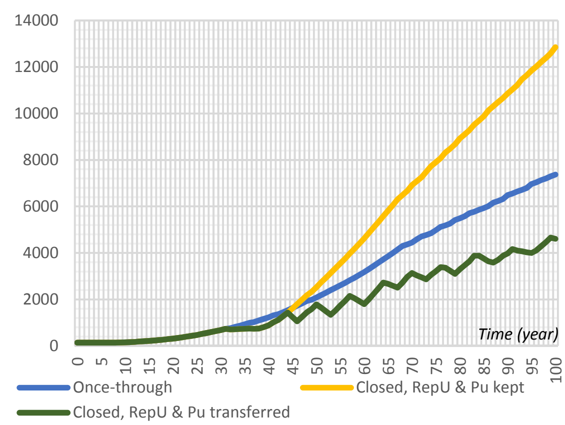

Fig. 2. Proliferation concerns (weapon significant quantities) of once-through cycle, closed cycle with RepU & Pu kept in the country, and closed cycle with RepU & Pu transferred out of the country.

2.3 Results

Equation (1) shows that different level of proliferation risk caused by the end-user state will affect its nuclear cooperation with the service provider due to the export control restrictions towards proliferation-prone countries. This effect is presented in Figure 3, which presents the relative bilateral cooperation corresponding to each choice of fuel cycle.

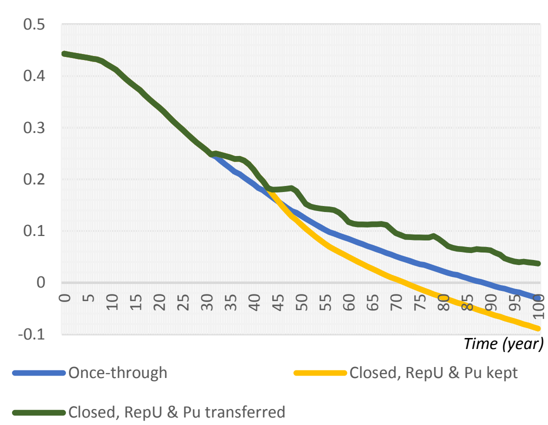

Fig. 3. Relative bilateral cooperation in case of once-through cycle, closed cycle with RepU & Pu kept in the country, and closed cycle with RepU & Pu transferred out of the country.

On the other hand, the effect of favorable and unfavorable public acceptance of nuclear energy was examined through modifying the socio-economic factors involving in Equation 2. As mentioned in the previous Section, unfavorable reception of nuclear energy by the public can induce delay in the implementation of the nuclear power program, as well as has negative impact on the bilateral nuclear cooperation between the end-user and its fuel supplier. Such delays and negative impacts, in their turn, will lower the net benefit of nuclear energy to the end-user. Such decrease in financial return of the nuclear program is presented in Fugure 4.

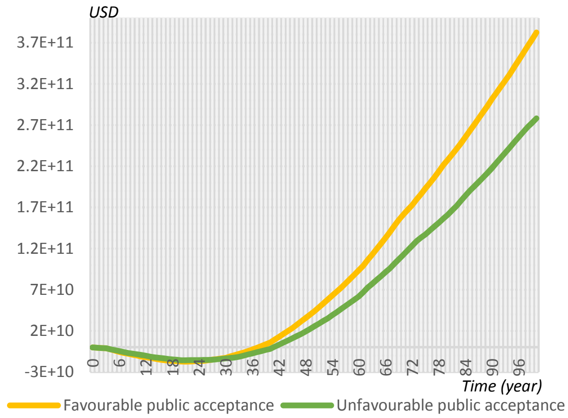

Fig. 4. Net benefit in case of favorable and unfavorable public acceptance (once-through cycle).

3. Conclusions

A system dynamics model of nuclear fuel cycle was developed in order to examine the trans-boundary and domestic effects related to the socio-economic aspect of the fuel cycle. The significance and coefficient of the socio-economic factors were determined using statistical analysis of historical data. Preliminary results show the definitive effect of such factors on the net benefit of the nuclear fuel cycle and its expansion in relation with the nuclear cooperation between the service provider and the end-user. Thus, future models need to incorporate such features in order to provide a more comprehensive look of the fuel cycle.

It should be noted that the system dynamics model presented here will be further developed to cover other socio-political factors, especially ones that have implications on nuclear nonproliferation. Further benchmarking and expert consultation will also be carried out to verify the appropriateness of the model.

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