Study of visualized simulation and analysis of nuclear fuel cycle system based on multilevel flow model

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Abstract Complex energy and environment system, especially nuclear fuel cycle system recently raised social concerns about the issues of economic competitiveness, environmental effect and nuclear proliferation. Only under the condition that those conflicting issues are gotten a consensus between stakeholders with different knowledge background, can nuclear power industry be continuingly developed. In this paper, a new analysis platform has been developed to help stakeholders to recognize and analyze various socio-technical issues in the nuclear fuel cycle system based on the functional modeling method named Multilevel Flow Models (MFM) according to the cognition theory of human being. Its character is that MFM models define a set of mass, energy and information flow structures on multiple levels of abstraction to describe the functional structure of a process system and its graphical symbol representation and the means-end and part-whole hierarchical flow structure to make the represented process easy to be understood. Based upon this methodology, a micro-process and a macro-process of nuclear fuel cycle system were selected to be simulated and some analysis processes such as economics analysis, environmental analysis and energy balance analysis related to those flows were also integrated to help stakeholders to understand the process of decision-making with the introduction of some new functions for the improved Multilevel Flow Models Studio, and finally the simple simulation such as spent fuel management process simulation and money flow of nuclear fuel cycle and its levelised cost analysis will be represented as feasible examples.

Keywords Multilevel flow model, Nuclear fuel cycle, Levelised cost analysis, Functional modeling method

CLC numbers F407.23, TM623

1 Introduction

In order to deal with the challenges of environmental degradation and energy shortage of the world, more and more attention is paid to the issues of energy, environment and sustainable development. Sustainable development objective cannot be realized without giving enough attention to energy analysis of all energy alternative options, as prelude to energy policy. The enactment of energy policies to achieve sustainable development objective cannot be realized without the participation of wide range of stakeholders including different domain experts. Especially the decision-making regarding nuclear power issues raises greater social concerns and conflicting opinions because of the lack of understanding and consensus between different stakeholders with different knowledge background. Today, it is recognized that the communication between different stakeholders is at least same important as the nuclear technology progress for the future of the nuclear power industry. How to cognize and understand those nuclear energy related technologies and systems is the key to communicate with the stakeholders to promote consensus building and to provide well-grounded basis for appropriate decision-making.[1]

According to the theory of human cognization by Saeki,[2] people cognize the outside world through a process as depicted in Fig.1.

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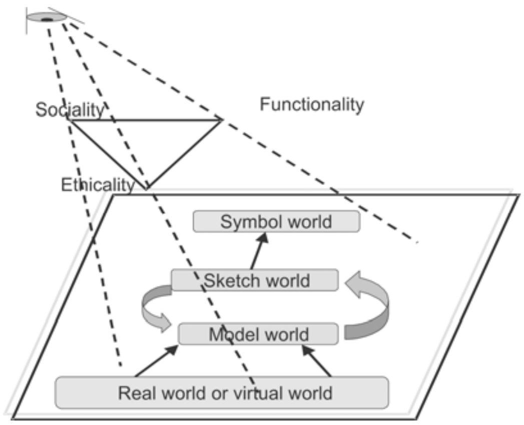

Fig.1 Process of cognition of the outside world.

This figure shows how people view the world in three different categories, real world, sketch world and symbol world. The real data depend upon the people from real world are converted into a simplified sketch or model as the media and tool of thinking to describe the real world in the brain of people. The symbol world, a more abstractive representation of the real world is adaptable to analyze and communicate with no vagueness and misunderstanding. The communication and education with other people require the free move amongst those three worlds. The communication process with other people involves conveying the sketch and symbol world to the acceptor, the acceptor will imagine the real world based on the sketch and symbol world in his brain, then move to the symbol world and real world to verify the obtained knowledge. If it is not consistent, it will repeat the process till the results are consistent. Using what kind of model or sketch to describe the real world is the crucial problem to effectively communicate and comprehend the real world.

J.Rasumssen[3] promoted abstraction hierarchy (AH) theory, which can provide help in cognizing and analyzing complex system. And it is supported by empirical studies and being an important element of cognitive engineering. The AH was used by American nuclear power industries after the Three Mile Island accident in their efforts to improve the reliability of the human-machine interaction and was later adopted by the Japanese nuclear industry in the conceptual development of a new generation of control room.[4] Lind originally proposed Multilevel Flow Model (MFM) as an attempt to formalize the AH, it is now seen as an independent development based on the same basic ideas of levels of means-end and part-whole abstraction as the AH.[4]

MFM, a graphical functional modeling method, uses graphical flow symbols to hierarchically represent the goal-function relation and cause and effect between different functions to help user to recognize, analysis and diagnose the complex process system. It has been traditionally applied for various process plants to reduce various operation support systems such as signal validation, alarm analysis, fault diagnosis, operation procedure, etc[5,6]. The authors have been developing a universal graphical tool software, MFMS to help user to apply MFM in process control and fault diagnosis.[7] The authors will extend the application of MFM to achieve that the relevant social-technical issues listed in Table 1 can be represented and analyzed in MFM model, because the nuclear fuel cycle system (NFCS) as an energy and environmental system also has the same morphological character as that of the process plant such as flow networks of mass, energy and information in the process system. The user can review every issue's goals, functions and components, and fix the reasoning logic about malfunctions and predict how systems would behave under various conditions to provide support for understanding and decision-making.

In order to achieve above goals, the authors proposed an analysis platform integrating relevant analysis tools affiliated to the database of MFM as a bridge to offer a common basis for discussion and communication about nuclear fuel cycle system to improve the consensus between different stakeholders.

The preliminary study of visual presentation of NFC system and the relevant issues, which concerns stakeholders and is needed by decision-making based on MFM, is given in this paper. It includes some improvement of MFM to accomplish the new tasks, and some experimental examples are given. The reasoning and diagnosis about nuclear spent fuel management based on MFM is also implemented as a feasible example.

The remainder of this paper is organized as follows. The new analysis platform for the analysis of nuclear fuel cycle issues by introducing the MFM is described in Section 2. In Section 3, some application examples are given, including that a micro-process and a macro-process of nuclear fuel cycle system are simulated and some analysis method processes are also integrated based on the MFM platform. The conclusions and future work are described in Section 4.

Table 1 Various issues relating to the nuclear fuel cycle in Japan

No.	Issues	Explanation
1	Security to obtain uranium resource	How to procure sufficient natural uranium from abroad to meet the demand of nuclear power?
2	Spent fuel reprocessing	How to effectively recover fuel from spent fuel?
3	Spent fuel storage management	Increased accumulation of spent fuel brings about the problem of storage and reprocessing.
4	Nuclear non-proliferation	How to introduce resistive measure against the nuclear proliferation and terrorist attacks?
5	Disposal of HLW	What kind of technique is needed for safe disposal of high-level radioactive waste?
6	Financial issues	How much investment will be needed for construction of nuclear fuel cycle and who will pay for it?
7	Public acceptance	How to improve the public acceptance for the construction of various nuclear fuel cycle facilities?

2 The MFM-based analysis platform for nuclear fuel cycle issues

In this section, the essential of MFM and the expansion of MFMS are briefly described, and the MFM-based analysis platform for nuclear fuel cycle is also proposed here.

2.1 MFM

MFM (Multilevel Flow Models), proposed by Morten Lind,[4] is a graphical representation method for describing the process system from its semiotic aspect like goals and functions of technical systems. In MFM a system is represented by its goals, its functions (to attain the goals) and its components (to realize the functions). These three aspects of a system form the hierarchy of Means-Ends versus Whole- Part relationships. The aim of MFM is to provide a systematic basis for understanding the relation of means-ends and whole-part decompositions for the modeling of complex industrial plant from the semiotic aspect.

There are several function types like source, transport, sink, etc., as shown in Fig.2 for their graphical symbols. For the energy and environment system, the energy product converted from other type of material or energy is also through a series of functions of energy source, energy transport and energy storage to the final consumers. They are connected together to describe some flow structures, i.e. mass flow structure, energy flow structure, and information flow structure of the process. The MFM's flow structures indicate the functions for achieving the goals. Therefore, the connections between the goal and the flow structures of mass and energy and goals indicate goal-achievement relations. The functions connected by the flow of mass and energy give the causal links in the process system.

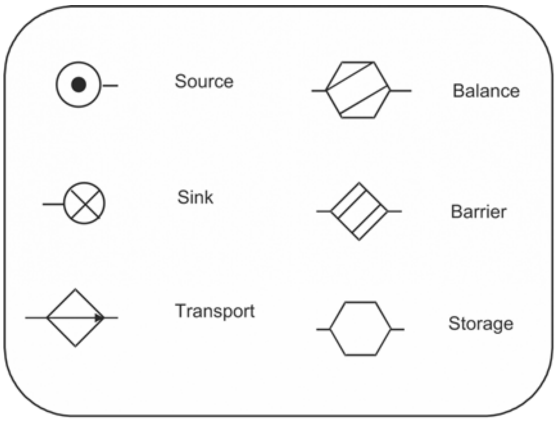

Fig.2 Symbols of functions used to describe mass flow and energy flow in MFM.

By noticing the advantages of explicit description of goals and functions by the graphical MFM models, there have been many studies of MFM applications in the area of process control such as fault diagnosis, alarm analysis and procedure generation of process plant.[4-6] Because the MFM methodology is a model-based visual knowledge representation approach, its multiple levels of goal and achievement relationship make the complex system to be easily cognized.[8] In general, it is also considered that the MFM can be utilized to describe and analyze various issues of complex processes where the energy flow and mass flow exist in the process, for example, municipal waste and resource recycle system, natural gas transportation management system, and nuclear fuel cycle system, etc. In order to support the wide utilization of MFM to model those processes, a graphical tool software prototype, MFMS (Multilevel Flow Model Studio), has been developing by the authors.[7] The MFMS is an integrated graphical interfaces system, which provides assistance from cover to cover, namely, modeling system and realizing final application for monitoring, diagnosis and operational instruction. In MFMS, there are many multimedia technology and intelligent agents applied to help the user to understand the complex operation system.

2.2 Expansion of MFMS to model nuclear fuel cycle

Nuclear fuel cycle is a series of complex processes as shown in Fig.3. There are many process steps in the nuclear fuel cycle: mining, milling, conversion, enrichment, fuel fabrication, reprocessing, waste disposal, etc., and there are many mass flow, information flow, and energy flow. Those flow characteristics can be described by flow conception of MFM, and expressed as the hierarchical flow structure of goal and function of nuclear fuel cycle. All the actions of the people have its own goals, which construct a goal structure. Typically, the goal structure is complex, comprising different types of goals, and achieved in different ways. For instance, production goals prescribe what has to be achieved (in normal operation), whereas safety goals prescribe something that has to be prevented. Those issues listed in Table 1 can be classified into goal structure, and one can use MFM's goal-function analysis to hierarchically represent those issues. The general goal of the cycle system is to achieve sustainability of energy, and the general goal is achieved by four sub-goals, i.e. environment friendliness, economy competitiveness, resource utility and social acceptance. The issues of 1 and 2 listed in Table 1 belong to resource utility issues, the issues of 3, 4 and 5 belong to environmental ones, the issue of 6 belongs to economical ones and the issue of 7 belongs to social ones. As for the different stakeholders, the general public primarily shows solicitude for the social issues, the investors take care of the economical competitiveness issues and the government focuses on the resource utility issues.

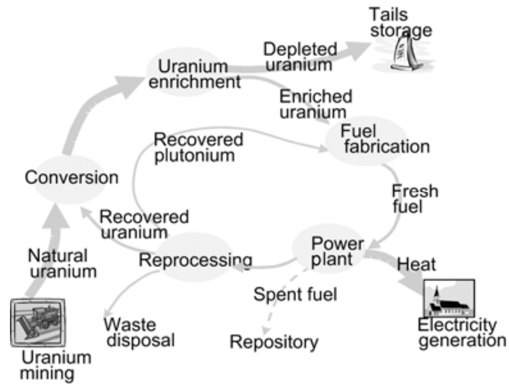

Fig.3 Nuclear fuel cycle system.

Concretely, there are many transportation process, recycle process and transformation process in nuclear fuel cycle system, i.e., changing one kind of material to another kind of material, transforming heat energy to electricity energy and even transforming mass to energy. To describe and implement various analysis for the various issues of nuclear fuel cycle as shown in Table 1, the equipped functions of the present MFMS cannot meet the requirements to deal with the nuclear fuel cycle issues because of their peculiarities as listed below:

a) there are many optional or alternative processes,

b) there are various transformation processes from mass to energy, from original mass to the new material to be generated, and the mass flow is not necessary to be balanced, and

c) the cost analysis is related with money flow taking account of discounting due to interest and time.

In order to handle those peculiar processes, some new symbols of MFM function are introduced in this study to describe new functions as seen in Fig.4 by expanding the original MFMS. They are "reaction

function”, “switch function”
and “conversion function”, as described below.

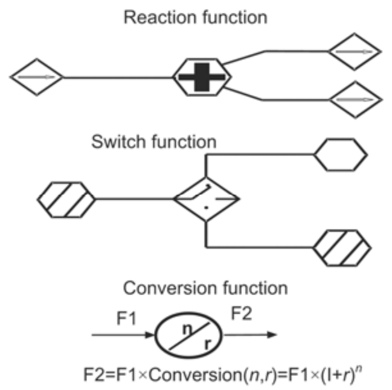

Fig.4 New symbols for MFM.

2.2.1 Reaction function

The “reaction function” represents the transformation process of reaction like nuclear fission reaction or chemical reaction where new material is produced and the input is not necessary to be balanced with the output. This function is different from “balance function” which describes the balance relation between the sides of both input and output. The “reaction function” will be used to represent an unbalance process with new material generated.

2.2.2 Switch function

The “switch function” represents that the output of the function has multiple choices according to different conditions, and it is applied to describe the options of alternative scenarios. It is used to deal with different simulation scenarios. It can be also used to describe on-off switch, in order to model dynamically changeable process of complex industrial systems by setting different options. This is a convenient symbol for analysts to evaluate and compare different kinds of scenarios.

2.2.3 Conversion function

The “conversion function” shows that the output flow and input flow of the matters have the same nature, but the value of the matter will be changed through the function. Here the conversion function is introduced specially to represent the time cost of money in money flow of MFM, like the discount function in the monetary terms used in economical analysis. It has forward or backward conversion function according to the positive value or negative value of n, where n represents the duration time, and r represents the discount rate.

2.3 The MFM-based analysis platform for nuclear fuel cycle

The word “platform” means versatile knowledge representation to help various analysts of different specialities to reorganize relevant knowledge of complex nuclear fuel cycle system in accordance with their specialities. Because the MFM methodology is model-based visual knowledge representation approach, its multiple levels of goal and function make the complex system be easier cognized.[8] Here the authors will propose a new analysis platform based on MFM as seen in Fig.5. The primary benefit of the platform is expected to use the MFM model to accurately model and analyze the complex system as done as in traditional application in fault diagnosis. The second benefit of the platform is expected to use the new improved functions to clearly describe the alternative options under different scenarios that will be reviewed in decision-making. The third benefit is expected to use multimedia technology to describe the detailed functions or components to help user to understand the complex cycle system. The platform based on MFMS is composed of three components: Symbol Editor is used to edit MFM model, Configure Assistant is used to setup calculation and consequence relationship between functions in the perspective of assessment, and Executor Program is used to display the results of assessment or diagnosis. One constructed MFM model may have different executive results because of different setup in Configure Assistant according to different purposes. The platform can implement cost analysis, environment analysis, and so on. Those analysis methods are quantitative relations between functions, those quantitative equations can be inputted in the parameters of each function as done in fault diagnosis.[9] Based upon this platform, the actual physical and chemical processes are converted into the functional models of MFM, and integrate various quantities of flow required by various analysis methods to handle the evaluation of the whole process system.

Firstly, we “simplify the actual process” by using MFM model to reduce abstractive representation of the individual processes. Then we will proceed to the introduction of individual analysis tools such as the evaluation of environmental hazard, cost estimation, etc., in the MFMS. In fact, the finished MFM model is a huge database including audio file, video file and various information needed by various analyses, which is organized by hierarchical goal. And finally the visual display of analysis results will be offered for stakeholders with different knowledge background to communicate and make decision.

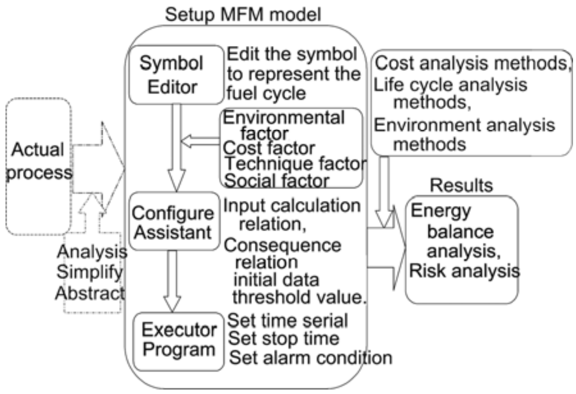

Fig.5 Analysis chart of nuclear fuel cycle based on MFM.

In original application of alarm diagnosis, the states of functions are set up as in Table 2.[9] In the platform, the authors will add the item of parameter relation, in addition to the item of state condition, to set up the calculation function between relevant functions to simulate the process. For example, the total amount of CO_2 emission is equal to the sum of the entire amount of CO_2 emission of relevant functions. In the improved MFMS, the calculation relation is more flexible to be set up between relevant functions. This improvement makes the embedded analysis tools practicable, because the final result of analysis is represented in one mathematical function or a series of mathematical functions as well as the inputs are displayed in different MFM models.

These consequence relationship in terms of cause-effect rule of flow model and state conditions are stored in a database which is based on the XML file structure.[7] The relevant video, audio and picture can be affiliated with the state that will be reviewed by the user.

In fact, the presented data to the user is easy to understand and automatic. For example, to produce one kilogram of uranium enriched to 3.5% ^{235}U requires 4.3 SWU (Separative Work Unit) if the plant is operated at a tails assay 0.30%, or 4.8 SWU if the tails assay is 0.25% (thereby requiring only 7.0 kg instead of 7.8 kg of natural U feed). Enrichment costs are related to electrical energy used. The gaseous diffusion process consumes about 2400 kWh per SWU, while gas centrifuge plants require only about 60 kWh/SWU. These data relation can be directly shown to the user, and the user can select the different parameters and different options. But the calculation function in MFM is complex as follows.[10]

$$S=V(X_p)+WV(X_w)/P-FV(X_f)/P,$$

$$V(X_i)=(2X_i-1)\ln(X_i/(1-X_i))$$

where the subscript i stands for f, p, or w.

$$W/P=(X_p-X_f)/X_f-X_w,$$

$$F/P=(X_p-X_f)/(X_f-X_w)$$

where X_f=weight fraction of ^{235}U in feed material, X_p=weight fraction of ^{235}U in the product (desired enrichment), X_w=weight fraction of ^{235}U in the waste stream (tails assay).

Table 2 Flow function states

Flow function	States	Condition
Transport	loflow	$F<F_{low}$
	hiflow	$F>F_{high}$
Storage	lovol	$V<V_{low}$
	hivol	$V>V_{high}$
Balance	leak	$\sum F_{in}>\sum F_{out}$
	fill	$\sum F_{in}<\sum F_{out}$
Barrier	leak	$F>0$
Source	lovol	$V<V_{low}$
	hivol	$V>V_{high}$
Sink	lovol	$V<V_{low}$
	hivol	$V>V_{high}$

It is not easy to understand above equation or not necessary to understand the calculation process for general decision-maker. The advantage of using the MFM is that the MFM model can accurately simulate the complex system and meantime provide the visual functional presentation in different levels for different stakeholders.

3 MFM application for nuclear fuel cycle

In order to handle various socio-technical issues on nuclear fuel cycle system, the authors set up a comprehensive analysis framework from “cradle to grave” along fuel chain, in which all the individual processes of the fuel cycle system are involved ranging from mining to conversion and enrichment, and to final disposal. The mass flow and energy flow existing in different steps of the life time can be clearly represented. For instance, in respect of the CO_2 emission or radioactive dose of every step, those data provide the input preparation for the following environmental analysis. The simulation for NFCS is a burdensome task. In this section, the authors only illustrate the MFM model of micro-process and macro-process as feasible examples. The simulation and diagnosis cases about spent fuel management and cost analysis tool are also examined with available data.

3.1 Modeling nuclear reaction process in reactor

Nuclear fission is a special reaction in the nuclear power reactor in which a heavier unstable nucleus (fissile material) would be divided into two or more lighter nuclei, with the release of substantial amounts of energy by the collision of slow neutrons.[9] An example of such nuclear fission process is shown in Fig.6. As shown in Fig.6, when a neutron collides with one ^{235}U particle, the ^{235}U particle splits into ^{141}Ba and ^{92}Kr as fission products and results in the generation of three neutrons. This is the source of enormous energy generation. Some of the neutrons produced by this ^{235}U fission will be absorbed in the isotope ^{238}U (fertile material) to produce a nucleus of ^{239}Pu, a fissile material which also gives rise to the fission reaction by the same way as ^{235}U particle. The fission products are atomic nuclei of different elements formed from the protons and neutrons originally comprising the nucleus before its fission. These fission products are highly radioactive materials and become the waste of nuclear energy production.

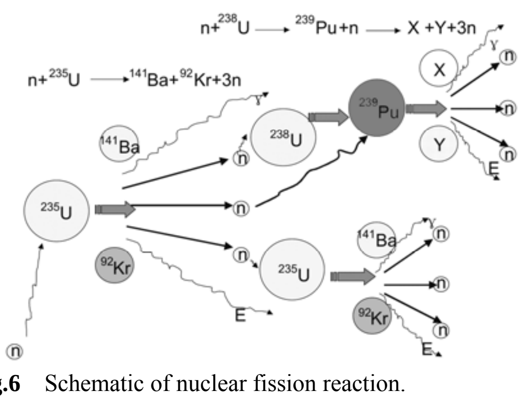

Fig.6 Schematic of nuclear fission reaction.

When the authors consider the nuclear reaction within the context of nuclear fuel cycle system, it is rather necessary to analyze the following itemized points:

(i) What are the constituents of nuclear fuel, i.e. fractions of fissile materials (^{235}U, ^{239}Pu) and fertile materials (^{238}U)?

(ii) How much thermal energy output will be produced from power reactor?

(iii) How much fissile materials are consumed, how much are still left, and how much fertile materials will be converted into fissile ones for a certain period of nuclear power operation?

(iv) How much fission products will be produced during reactor power operation? And how to classify the nature of various fission products?

The answers to the above problems are not obtained directly from Fig.6, but will be made by conversion of Fig.6 into the MFM model of the nuclear reaction processes as in Fig.7, with the provision of analysis tools to settle those questions (i) to (iv). In Fig.7, there are four flow networks E1, M1, M2, M3 with various functional relations depicted by the definitions of the symbols as illustrated in Table 3. The main goal of E1, the energy flow of the nuclear fission process, is Go1 (generate energy). It is achieved by E1 (energy flow), which describes the transport of energy from particles to cooling media. E1 is supported by Go8 and Go9, which are fissile reactions and generate energy. Go8 is archived by M1, a fissile mass flow. Go9 is archived by M2, a fertile mass flow. M1 and M2 are all conditioned by M3, neutron flow to provide neutrons for the fissile and fertile reaction. Meantime, M1 and M2 maintain neutron resource. Therefore Go3 and Go4 (Go6 and Go7) thus support each other and establish the chain reaction. Some of the produced neutrons are used to maintain chain reaction and some are used to breed ^{239}Pu(Go2).

The above MFM model describes the elementary process of nuclear chain fission for Fig.6, the constructed MFM model in Fig.7 can offer visualized display of the necessary data and their relationship to obtain the answer for the questions (i) to (iv).

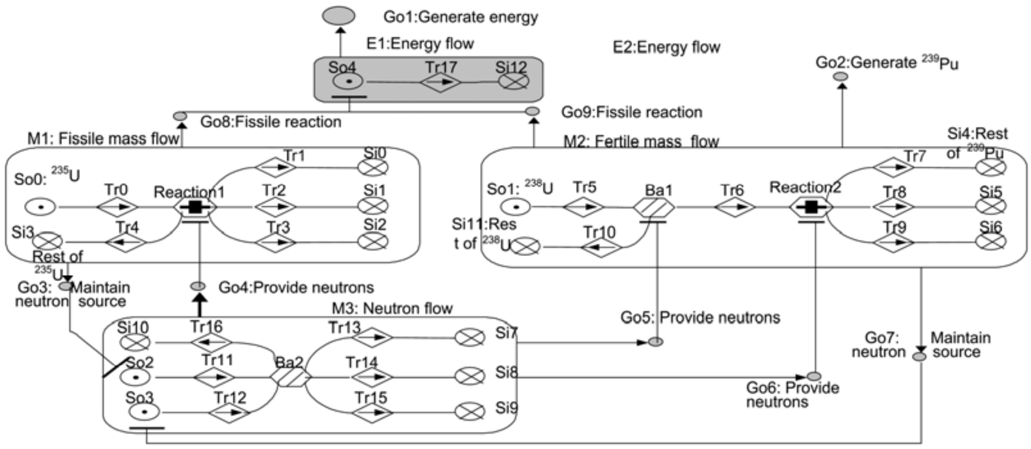

Fig.7 MFM model to describe chain nuclear reaction and fissile generation by the mediation of neutron. “Go” represents goal, “E” represents energy flow, “M” represents mass flow.

Table 3 Definition of function in MFM model of chain reaction

Name	Explanation of function
So0	^{235}U fuel source
So1	^{238}U fuel source
So2	Neutron source from fissile reaction of ^{235}U
So3	Neutron source from fissile reaction of ^{239}Pu
So4	Energy source with particles
Tr0, Tr4, Tr5, Tr6, Tr10	Transport
Reaction1	Fission reaction of ^{235}U, and generate energy
Tr1, Tr2, Tr3	Transport particle of ^{141}Ba, ^{92}Kr and neutrons respectively
Si0,Si1,Si2	Sink of particles of ^{141}Ba, ^{92}Kr and neutron respectively
Si3,Si4,Si11	Sink of remaining ^{235}U, ^{238}U and ^{239}Pu respectively
Si5, Si6	Sink of fissile products and neutron respectively
Ba1	^{238}U capture one neutron and generate ^{239}Pu
Reaction2	Fission reaction of ^{239}Pu, and generate energy
Tr7,Tr8,Tr9	Transport^{239}Pu,fissile products and neutron respectively
Ba2	Balance of neutrons
Tr11,Tr12	Transport neutron
Tr13, Tr14, Tr15	Transport neutrons to ^{235}U, ^{238}U and ^{239}Pu respectively
Tr16	Transport neutrons
Si7,Si8,Si9	Sink of neutrons, captured by ^{235}U, ^{238}U and ^{239}Pu respectively
Si10	Sink of nonreacted neutrons realized by environment
Tr17	Transport energy by gamma ray or other particles
Si12	Sink of energy

3.2 Modeling whole nuclear fuel cycle

Here the authors consider the MFM model to illustrate the whole process of nuclear fuel cycle in Japan. There are two reactor types in Japan, PWR and BWR. The necessary fresh fuel assembly for the reactor is produced in fuel fabrication facility in Japan. The natural UF_6, enriched UF_6 and enriched UO_2 can be imported from abroad. The process of fuel flow can be depicted as shown in Fig.8.[10] Natural UF_6 can be shipped from North American Facilities to enrichment facility in Japan. The enriched UF_6 will be transported to conversion facility to convert UF_6 to UO_2. Then the enriched UO_2 are transported to fuel fabrication facility to make fuel assembly to supply for the power reactors. After reaction in PWR or BWR, the fuel will become spent fuel and will be transported to interim storage. Then the cooled spent fuel will be reprocessed in the reprocessing facility in Japan. After reprocessing, the spent fuel will be divided into three parts. One part comprising uranium will be transported to conversion facility, then to enrichment facility to recycle use of uranium as nuclear fuel. The second part including plutonium will be transported to fabrication facility to make mixed oxide fuel for nuclear reactor. The last part including high-level radioactive waste will be transported to high-level waste disposal facility in Japan.

In order to trace the problems of security to obtain the uranium resource, spent fuel management and life cycle economics assessment mentioned in Table 1, the authors describe the whole process by MFM as shown in Fig.9. The main goal of the system is to generate energy. There are several sub-goals to provide electricity power for various nuclear fuel cycle facilities such as enrichment facility. The definition of function is shown in Table 3.

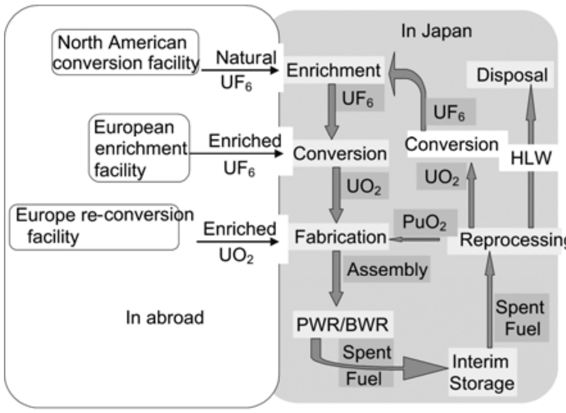

Fig.8 Nuclear fuel cycle situation in Japan.

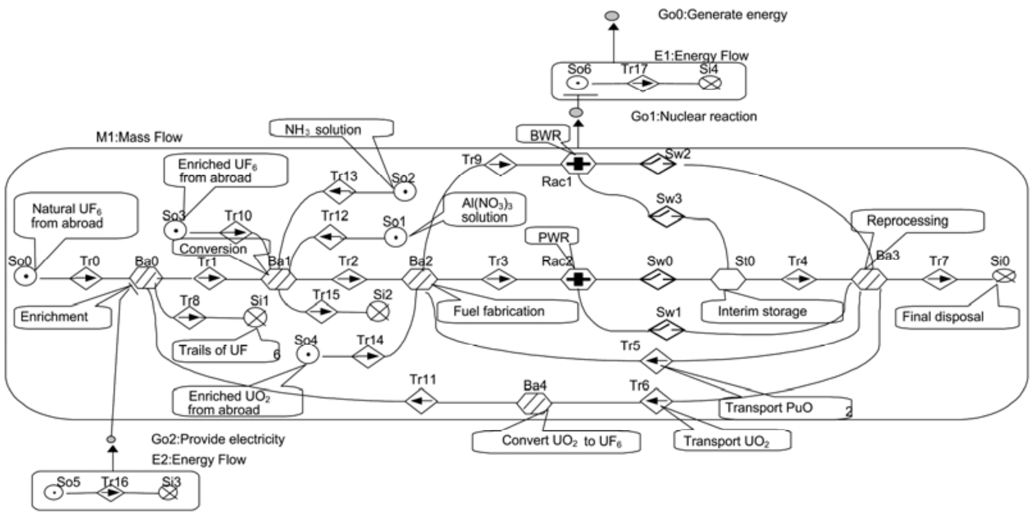

Fig.9 MFM model of nuclear fuel cycle of Japan.

In the MFM model, the main goal is Go0, generates energy. The goal is archived by E1, and E1 presents that there is energy transport from reactor to electricity net. E1 is conditioned by Go1 (nuclear reaction), and Go1 is archived by M1 (fuel cycle flow structure). The flow network M1 describes the whole mass flow of uranium from North American conversion facility to the final waste disposal. The network E2 describes the electricity power supply from external electricity source to enrichment facility. In the network M1, the function definition is shown in Table 4. It should be noted that the new function, "switch function", is used here. Sw0, Sw1, Sw2 and Sw3 present that the spent fuel transportation has some options to be selected according to the actual situation, how much transported to interim storage or how much directly transported to reprocessing facility.

Table 4 Explanations of functions in MFM model of nuclear fuel cycle

Name	Explanation of function
So0	Natural UF_6 produced in North American conversion facility
So3	Enriched UF_6 from Europe
So4	Enriched UO_2 from Europe
So1	Tank of $Al(NO_3)_3$ solution
So2	Tank of NH_3 solution
So5	External electricity resource
So6	Energy source in reactor
Tr0,Tr10, Tr14	Ship
Ba0	Using enrichment techniques to get high concentration ^{235}U to3%-4%
Tr1	Transport enriched UF_6
Ba1	The enriched uranium hexafluoride is chemically converted to pure uranium dioxide powder
Tr2	Transport UO_2
Ba2	Through a series of procedures to get fuel assembly for nuclear reactor
Tr3, Tr9	Transport fresh fuel assembly
Convert B3	Fission reaction, generate energy and spent fuel in PWR
Convert B5	Fission reaction, generate energy and spent fuel in BWR
Sw0,Sw1, Sw2, Sw3	Represents that there are some option to transport how much spent fuel to reprocessing facility or to interim storage facility
St0	Interval storage in cooling pool or dry stores
Tr4	Transport spent fuel
Ba3	Recovery U and Pu through dissolving and separation spent fuel, and produce HLW(in Reprocessing plant)
Tr7	Transport HLW
Si0	High-level-waste processing and disposal
Si1	Sink of UF_6 tails produced in enrichment process
Tr8	Transport tails
Si2	Solid waste disposal facility
Si3	Enrichment facility
Si4	Electricity net
Tr5	Transport PuO_2
Tr6	Transport UO_2
Ba4	Convert UO_2 to volatile uranium UF_6
Tr11,Tr12, Tr13,Tr15,	Transport
Tr16,Tr17,	Transport

3.3 Integrated analysis method and its data relationship

On the basis of MFM of micro-process and macro-process of nuclear fuel cycle, the authors can integrate some appropriate analysis methods to provide support for cognizing and making decision, as well as help the stakeholders to easily understand the logic and quantity relationship of these relevant issues. As mentioned above, nuclear fuel cycle is related with many components and many stakeholders, and different stakeholders have different focuses and interest about the cycle system. All those factors and issues are related with those intermediary flow processes, which can be represented clearly in the MFM model of those processes and the "MFM is easy to represent the process of flow”[4] means that it can represent the whole flow chain of the lifetime cycle. Therefore many lifetime cycle analysis methods can be simulated in MFM, and the authors can also select some important steps to analyze and compare.[11] The data relationship is shown in Fig. 10. The MFM model of nuclear fuel cycle system is established based on the mass flow and energy flow, and then the amount of CO_2 emission, cost and the radioactivity dose of every component, or other required quantity for analysis can be calculated. Those data simulation relationships will be setup in Configure Assistant in MFMS or stored in the parameters of corresponding function of MFM of the process in MFMS. When the analysis requires these data, they can be applied or naturally displayed in some formations to the stakeholders.

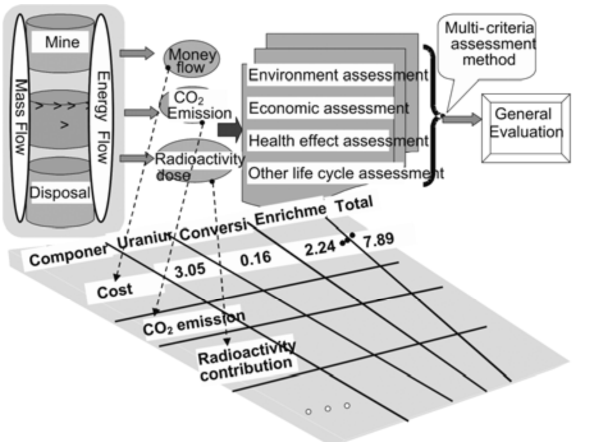

Fig.10 Data simulation relationship of sustainability evaluation.

As mentioned in Table 1, nuclear spent fuel system has significant influence on the environment and people's lives. It is a great concern in society and attention has been given to nuclear spent fuel. Using a model to review the process of generation, transportation and management of nuclear spent fuel is necessary for stakeholders to recognize and make a decision. The following gives the simulation and diagnosis result based on some supposed data by using MFMS.

3.3.1 Case of spent fuel management

The MFMS can diagnosis and simulate those flow processes, for example, the users can further analyze the quantitative relation of spent fuel based on the MFM model in Fig.9. From Fig.9, we know that sources of the spent fuel are PWR and BWR. There are two choices of how to deal with the spent fuel, i.e., to transport to reprocessing facility directly or transport to interim storage. Finally the spent fuel will be transported to reprocessing facility. After the reprocessing, the spent fuel will be divided into three parts and transported into different sink functions, as described in the first paragraph of Section 3.2.

Based on Fig.5, the authors select the mass flow parameter by setting the threshold value for alarms in Configure Assistant of MFMS to illustrate “bad spent fuel management”, and read the supposed data for spent fuel generation in Executor Program. There will be the following possible alarms displayed in MFMS: (i) inflow of spent fuel is bigger than the reprocessing capacity; (ii) inflow of plutonium is less than the anticipated value (this means there is the leakage of plutonium, or the risk of nuclear proliferation); (iii) the inflow of the sink of high-level waste is bigger than the capacity of disposal; (iv) amount of spent fuel is bigger than the capacity of the interim storage.

3.3.2 Levelised cost analysis based on MFM

The economics competitiveness of nuclear energy with different fuel cycle options is also an important issue as mentioned in Table 1. Although the economical analysis cannot reflect all perspectives of the system since some externalities’ cost cannot be included, the result of economical analysis plays an important and indispensable role in decision-making. Here the authors will simulate the process of lifetime levelised cost analysis of nuclear fuel based on MFM as follows.[12]

The authors assume that the fuel batch is charged into the core in 2000, a PWR fuel batch is 34.7, the burn-up is 33000MWd/t, after 3.34 years it will be discharged from the core and the discount rate is 5%. The parameters are as follows.

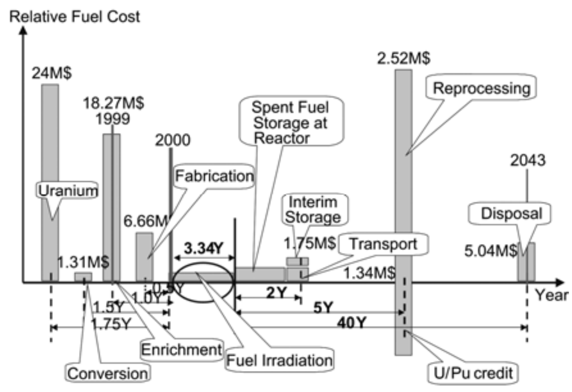

Fig.11 The time flow of nuclear fuel cycle cost.

Reactor electric power is 1285 MW, about 74.2% capacity factor, enrichment with 0.25% tails, thermal efficiency 33.8%, and not including cost of irradiation in reactor core. The time flow of nuclear fuel cycle cost is shown in Fig.11.

The time flow of the nuclear fuel cycle cost means that in order to produce electricity of 9.293×10^9kWh (=(33000MWd/t) × (34.7t) × 24000 kWh/MWd × 33.8%) in the period of 2000 to 2003 (here 24000kWh=1MWd), 24M$ was spent to purchase uranium ores on the time point of 1998, 1.31M$ spent for the conversion from "Yellow cake" to UF_6, 18.27M$ spent to enrich the UF_6, and 5.04M$ will be spent for the final waste disposal in 2043 as seen in Fig.11. The MFM model of the process can be depicted as shown in Fig.12.

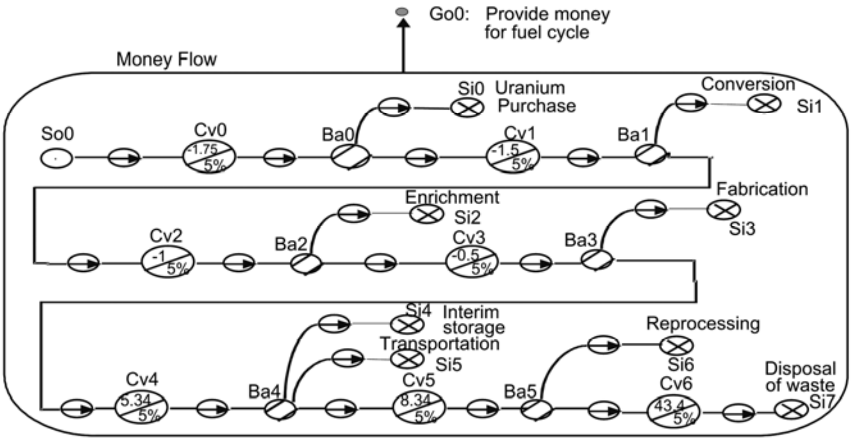

Fig.12 MFM model of money flow of nuclear fuel cycle.

The main goal of the money flow structure is to provide cost for fuel cycle. The money flow network describes the whole money flow from the investor to the every component on different time point through the conversion function (Cv0, Cv1 to Cv6). Based on the MFM of money flow (see Fig.12), which is the basic and indispensable part for any economic analysis, here the authors can simulate the levelised cost analysis of nuclear fuel cycle. The levelised cost analysis is recommended for assessing energy system by IAEA.[12] The data of the case came from Nuclear Energy Agency. All those money spent in different time points are converted into the present value in 2000 as seen in Table 5.

Table 5 Original expense and present value of every component

Components	Real value	Present value
Produce electricity (kWh)	9.293×10^9	8.577×10^9
Required fuel (t)	34.7	
Cost of purchase of uranium (M$)	24	26.14
Cost of conversion (M$)	1.31	1.41
Cost of enrichment (M$)	18.27	19.18
Cost of fabrication (M$)	6.66	6.82
Cost of transportation of spent fuel (M$)	1.34	1.04
Cost of interim storage (M$)	1.75	1.35
Cost of reprocessing (M$)	2.52	1.68
Cost of disposal of waste (M$)	5.04	0.61

According to the calculation method of levelised cost analysis, the levelised cost contribution of every component of nuclear fuel cycle is taken by using the discounted total amount of produced electricity to divide the present value of spent money, for example, 26.14M$/($8.577\times10^9$kWh)=3.05 mills/kWh presents that the cost used to purchase uranium ore contributes to the cost of electricity. The levelised cost contribution of all the individual components is shown in Table 6.

From the above results of levelised cost of individual components, the extent of the contribution of every component to the total levelised cost of per kWhe can be known, even if the availed data are not current data. All these calculation relationships will be described in improved MFMS's functions. If the different data for the above parameters are inputted, another result of alternative options will be gotten. It is easy for MFMS to calculate different options and give the comparison results to support the decision-making on the condition that the calculation relationship of analysis method is integrated in the MFM model. Here the authors primarily demonstrate the financial analysis methodology based on MFM, which is very important for people's decision-making, and the final selection result is easily received when the available data for alternative options are changed.

Table 6 The total fuel cycle cost in 2000 for the equilibrium batch (derived by summing up all the individual components)

Components	Cost (mill/kWh)
Uranium	3.05
Conversion	0.16
Enrichment	2.24
Fabrication	0.80
Transportation of SF	0.12
Interim storage	0.16
Reprocessing	1.96
Disposal of waste	0.07
U credit	-0.41
Pu credit	-0.26
Total	7.89

4 Conclusions and future work

In this paper, a framework of graphical analysis and communication platform for nuclear fuel cycle issues based on MFM are proposed by introducing some new symbols to improve the capabilities of MFMS to review various concerned issues from the viewpoint of general stakeholder. Then the authors introduced how the MFM models of micro process of fission reaction and macro process of whole nuclear fuel cycle can be described by the improved MFMS. The authors also gave the simulation and analysis of spent fuel management process based on MFMS and the simulation of levelised cost analysis of nuclear fuel cycle based on the MFM model of money flow to help user to understand relevant issues. The money flow and its analysis are first represented using MFM in this paper. This paper proved that MFM could be used in simulating nuclear fuel cycle system to provide help for understanding complex physical, chemical processes and various social-technology issues to help decision-making. The future work is to integrate other appropriate analysis methods to improve the platform to deal with various concerned issues mentioned in Section 1 based on the MFM. Especially, the authors will proceed to the problems of how to cope with increasing nuclear spent fuel bases on our proposed MFM model of spent fuel management issue. In the process, the authors will take account of economic, technical, social and environmental factors to consider different scenarios and options for analysts and decision-makers.

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