Accident Management of the Station Blackout at BWR by Using Multilevel Flow Modeling

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Abstract: Accident management is a key factor to ensure the defense in depth of the nuclear power plant. One of the requirement is an effective response planning, especially for the unexpected event when pre-defined countermeasures may fail. When operators encounter a planning task, they usually consider the problem within a context of intentions. It is important to apply model-based system to acquire plant's intentionality, which is necessary to manage planning related resources and further to generate plans. In this paper, we first demonstrate how multilevel flow modeling, a method of functional modeling can represent the intentional knowledge of a plant in terms of function and goal. Then we will investigate how the same representation can be used to identify alternative means to realize goals, which may be out of their original purposes considered in design but have positive effects on goal achievement. Based on a previous study, the alternative means generated by MFM can be further expressed as operating procedure, which can include series of human operations. An accident case that is similar with the Fukushima Daiichi accident, i.e. station blackout of a boiling water reactor, shows how MFM can be used to support the activity of response planning. Planning knowledge of the plant that contains functions, objectives, and their relationships is represented by an MFM model, based on which, several response plans are generated to achieve the goal of core cooling.

Keyword: Accident Management, Decision Support Systems, Multilevel Flow Modeling, Station Blackout

1 Introduction

Accident management is one of the key component of effective defense in depth of nuclear safety [1]. Lessons from the Fukushima accident indicate that there was not enough capability of responding for the unexpected situation, which were not explicitly addressed by the pre-defined measures such as emergency operating procedures (EOPs) [2]. During an unexpected event, one of requirement is an effective response planning to develop alternatives approach for achieving a goal, which needs human operators to consider the plant functions designed, including possible use of safety and non-safety systems even beyond their original intentions to return the plant to a controlled state. It must be admitted that it is hard for operators to identify such alternatives. In this setting, decision support systems may play a significant role in accident management by providing facilities for operators' tasks, especially their response planning.

When operators encounter a planning task, they generally consider the problem within a context of intentions, such as the purpose of component [3]. A good understanding of designed intentions of plant systems is important for operators to take advantage of system resources for response planning. To support operators, therefore, it is necessary to use a model to express the intentional knowledge about the plant. Multilevel flow modeling (MFM) is a functional modeling method for describing a complex system such as nuclear power plant (NPP), by which the intentions of systems can be represented in terms of goal, function, component, behavior, and relationship between them. Moreover, the same representation can be used to produce plans [4]. In a previous study [5], a system was developed based on MFM to generate procedures for accident situations. In addition, Inoue [6] investigated criteria to evaluate generated plans, which is also important for response planning.

In this paper, it will illustrate how MFM can be used to support the accident management, especially the activity of response planning. It will investigate the capability of MFM to identify alternative means. The method of generating procedures based on MFM will be also introduced. An accident case that is similar with the Fukushima Daiichi accident, i.e.

station blackout at a boiling water reactor (BWR) will be presented.

2 Multilevel flow modeling

2.1 Basic modeling theory

MFM [7][8] is a graphical modeling methodology for representing goals and functions of industrial process involving interactions between flow of material, energy, and information. Figure 1 shows its primary symbols.

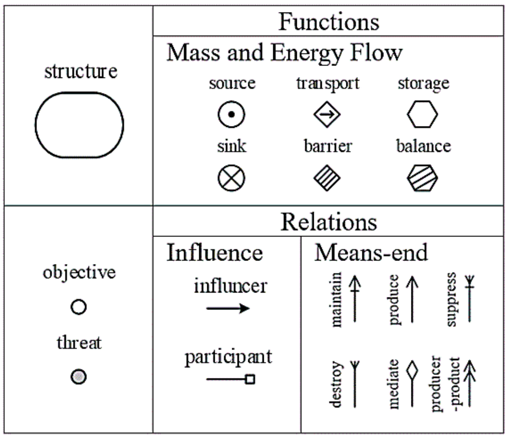


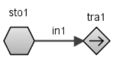
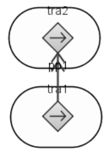
Fig. 1 MFM symbols

The concepts of means-end and whole-part decomposition and aggregation play a fundamental role in MFM that lead to a modeling in multiple levels of abstraction. Along the means-end relation, a specific end (goal or function) can be realized by means, which can be represented by functions in a suitable abstract level. On the other hand, different means-end structures are aggregated in the whole-part dimension to form a complete model.

2.2 Causal inference of MFM

In MFM, there are not only means-end relationships that can describe the realization between functions and goals, but also causal relationships to explain how the state of a function influences those of other function. The state can mean how far the performance of functions deviated from the desired norm such as high or low state of a transport. Gofuku [9][10] defined the cause-effect relations of states between functions as the influence propagation rules. There could be a lot of patterns of rules. Zhang and Lind [11] has recently updated them to make it possible to analyze the casualties on both whole-part and means-end dimensions. Table 1 shows examples of two categories of patterns. Note that there is a finite set of patterns because the MFM syntax constrains some illegal connections.

Table 1 Examples of influence propagation rules

Pattern	Cause	Consequence
 (whole-part)	sto1 high volume sto1 low volume tra1 high flow tra1 low flow	tra1 high flow tra1 low flow sto1 low volume sto1 high volume
 (means-end)	tra1 high flow tra1 low flow tra2 high flow tra2 low flow	tra2 high flow tra2 low flow no consequence no consequence

There is no isolated function or objective in an MFM model, which means all of them are either linked by causal relations or means-end relations. This ensures that the influence can be propagated along different MFM patterns. Therefore, if the abnormal state of a function or objective is assumed, then both the root causes and consequences can be inferred along many possible inferring paths.

3 Functional modeling of BWR

3.1 BWR and station blackout

The type of BWR is a kind of light-water reactors. Figure 2 shows the system configuration of a GE-Hitachi BWR which is the same reactor type of Units 2 to 5 of the Fukushima Daiichi nuclear power station. BWR has only one single power cycle, in which the steam is directly produced through the reactor core to drive the turbine-generator. There are various auxiliary systems that are designed to maintain a normal operation and to ensure plant's safety during the accidents.

As happened in Fukushima, the automatic actions of shutdown triggered by the earthquake successfully achieved and the control of reactivity had been achieved after the earthquake. Afterwards, the reactor cores still needed to be cooled because of decay heat generating. Although the earthquake damaged all off-site electrical power, the emergency diesel generators could maintain the cooling function until the tsunami came to damage them. As a result, the reactor lost all AC power for core cooling and other safety functions, a situation referred to as a station blackout (SBO) [12]. There is

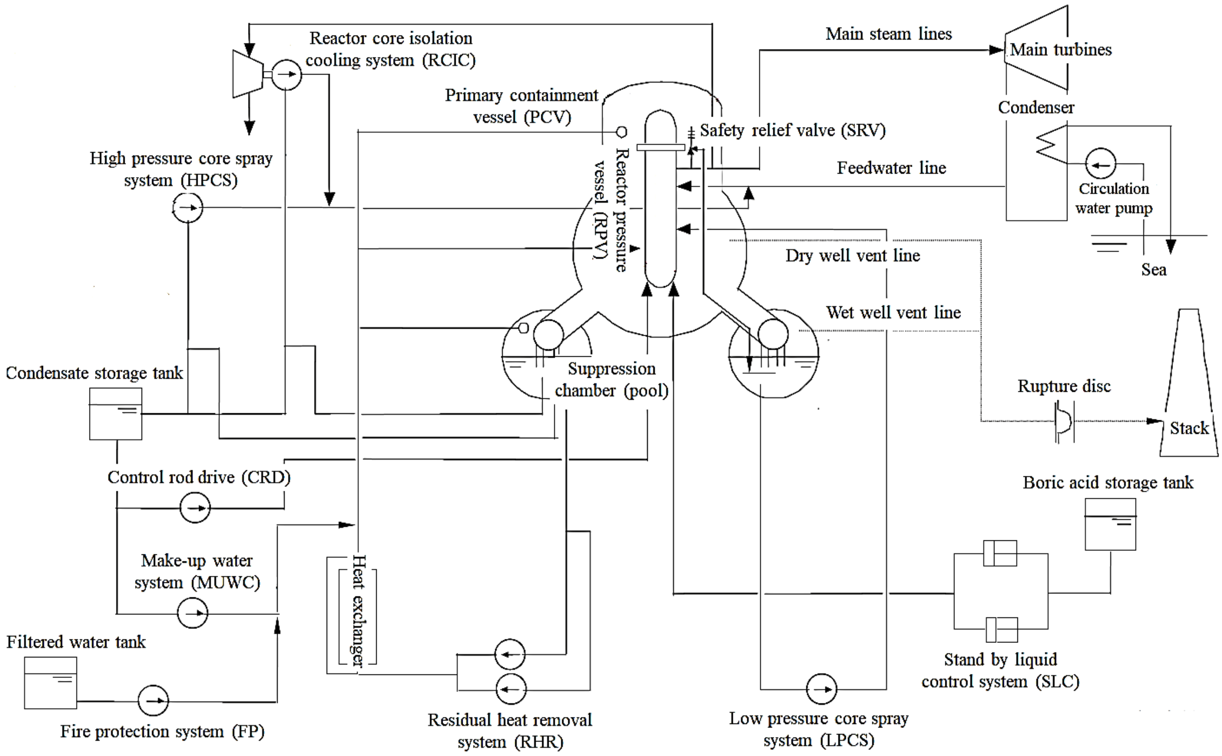


Fig. 2 The system configuration of a BWR plant

an urgency to identify the alternative strategies from the existing systems, which requires comprehensive knowledge about means-end framework of functions and goals as MFM represents.

3.2 MFM model of BWR at the onset of SBO

The operational goals of BWR in the disturbance are different from those in the normal operation. The functions may also change their functionality or turn unavailable. The state change of goals and functions indicate a shift of operational mode [13]. As shown in Figure 3, an MFM model of BWR in the mode of SBO onset is constructed, which describes the safety goals and available functions after the reactor shutdown but before SBO occurring.

3.2.1 System objectives

There are three safety objectives at the onset of SBO, i.e. to maintain heat removal from the reactor core (*obj6*), to depressurize the reactor pressure vessel (RPV) (*obj7*) and to depressurize the primary containment vessel (PCV) (*obj8*), which are all directly related to the energy flow functions in RPV and PCV and those between them.

3.2.2 Mass and energy flow of RPV and PCV

For the energy flow in functional structure *efs3*, the decay heat generated in the reactor core is regarded as the energy source (*sou4*). Four energy sinks can be identified for the heat transport. One (*sin9*) is provided by the injection system, which lets the energy in the water (*sto7*) consumed by additional coolant. The second sink (*sin29*) is resulted from the core spray system, by which the energy in the steam (*sto8*) can be released by means of steam condensation. The other two energy sinks represent consuming the energy stored in PCV (*sto10*) by containment spray (*sin11*) or venting (*sin12*).

The mass flow is represented by structure *mfs1*. There are four storage functions, i.e. the coolant (*sto3*) and the steam (*sto4*) in RPV, the water (*sto14*) in the suppression pool of PCV and the steam (*sto15*) in the suppression chamber of PCV are used to describe possible mass circulation. Since the power cycle is isolated, there are two barrier functions (*bar5* and *bar6*) isolating coolant and steam from the turbines respectively. The source and transport functions connected with *sto3* and *sto14* can be considered as the function interface between PRV or PCV and the auxiliary systems. For example, transport function *tra50* can represent the functions of the reactor injection systems.

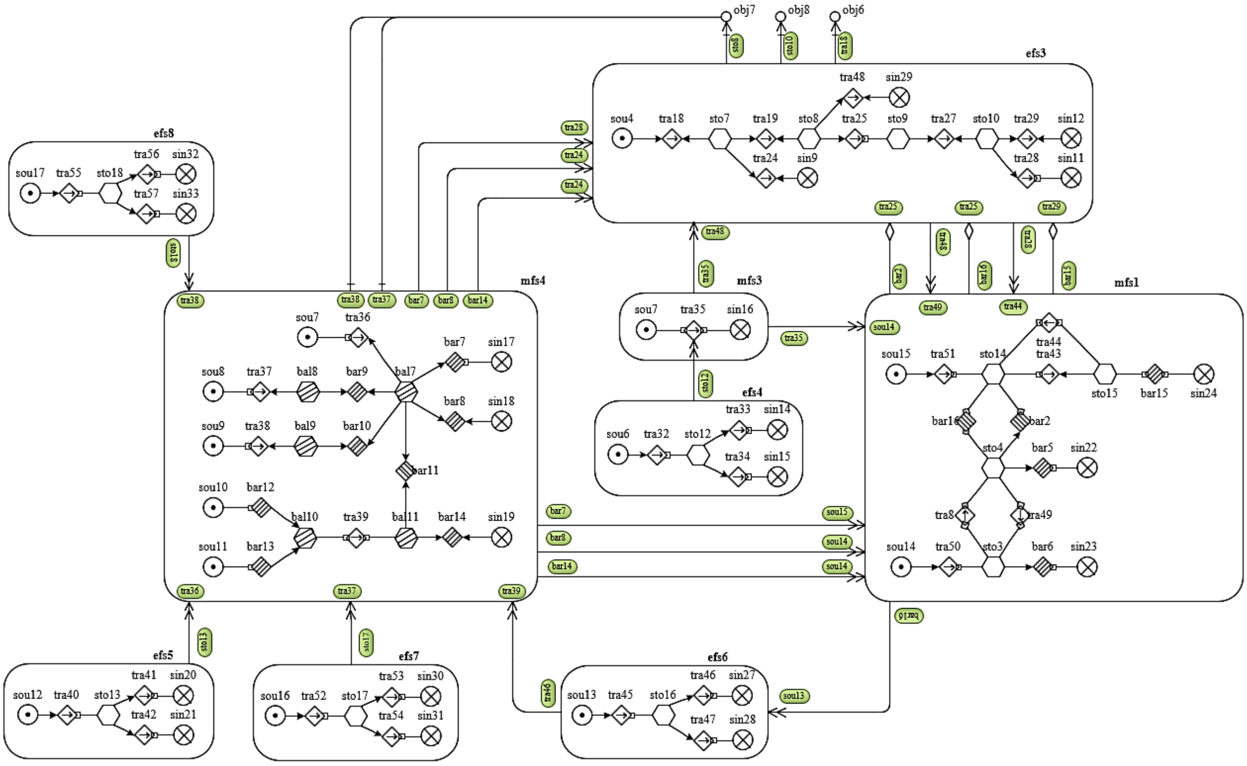


Fig. 3 MFM model of BWR at the onset of SBO

3.2.3 Modeling the auxiliary systems

Mfs3 represents the independent reactor injection systems, i.e. the high- and low-pressure core spray system in a high abstraction level. *Efs4* is the means of transport *tra35*, which involves in the conversion of electrical energy to rotational energy.

Mfs4 represents the safety systems involving in pipelines connection, which include reactor core isolation cooling system (RCIC), residual heat removal system (RHR), make-up water system (MUWC) and fire protection system (FP). There are five source functions representing various water sources of systems, and three sinks representing PRV or PCV. It uses several barrier functions to model the closed valves and some transport functions to model various kind of pumps. All of transport functions have means of electrical conversion that are the same with the form of structure *efs4* except for *tra39*, whose means represented by structure *efs6* is steam working of the RCIC turbine.

4 Response planning by MFM

Response planning refers to the cognitive task of developing an approach for achieving a goal [14]. In terms of MFM, it is a process of identifying means that is represented by functions to achieve a defined end. In most case, the means-end relationship of the systems has been prescribed in advance so that the response planning can be guided by some procedures. However, during the unexpected, when no designed means is able to fulfill their functionality to achieve a recovery goal, apart from repairing or replacing failed systems, it is needed to find an alternative means, which may be both within and beyond the design basis. Below it will show how MFM can be used to support this activity.

4.1 Identifying alternative means by MFM

It has been shown that MFM can represent mean-end relationship of a plant that is considered in plant design. For a given end, which can refer to an objective or a high-level function in the MFM model, there are two approaches to identify the alternative means. One is done by the basic feature of MFM, i.e. many-to-many mappings [15]. The second is to search means that has potential to causally influence goal achievement, which can be realized by casual inference of MFM.

4.1.1 Many-to-many mappings

Most systems have the feature of many-to-many mappings of means-end. It can be explained that the same end can be realized by many alternative means, which can at the same time be used to realize several ends [15]. A dummy structure of many-to-many mapping is shown in Figure 4.

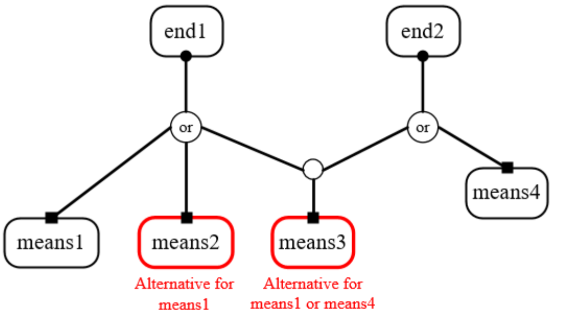


Fig. 4 Identifying alternative by many-to-many mappings

Therefore, an MFM model as shown in Figure 3 can describe some designed alternative means that are available in a given situation, subsequently be used for identifying about which of the alternatives to choose. These alternatives are usually considered in redundancy design. A typical example is transport function *tra24* in structure *efs3* of the model, i.e. heat removal by additional coolant, which has three alternative means according to the design, that is, high-pressure injection, low-pressure injection and RCIC injection, respectively.

4.1.2 Causal inference

A means should not only be used by an agent with the intent of achieving an end, i.e. a teleological aspect of the means-end relations, but also be able to produce it, which indicates the causal aspect [15]. In other words, the goal achievement can be caused or influenced by the change of states of some means.

When the state of a function cannot be changed by operations to fulfill a goal, it should be considered what state of what other functions can also cause the desired state. Here the latter functions can be defined as an alternative. As shown in Figure 5, this kind of alternative can be identified by using MFM causal inference [5][9][10][11]. The inference process can be iterative so that alternative means in lower abstraction levels can be identified. Note that a means may contain more than one function, whose states can only be inferred by matching influence propagation rules introduced in Section 2.

The first approach can only identify the alternatives that have been specified in design, whereas the second are useful when one tries to find means that may be out of their original intentions but have positive effects on our purpose. A particular interest is made to apply above methods to deal with the unexpected situations when designed means fail. Note that the many-to-many mappings of MFM can be applied in all the approaches above.

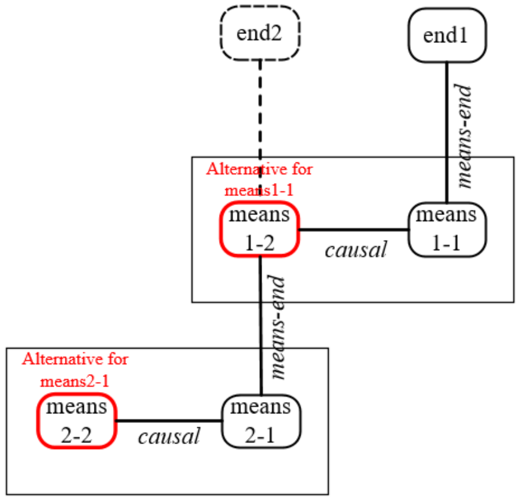


Fig. 5 Identifying alternative by causal inference

4.2 Producing alternative procedures by MFM

Although an MFM model represents only the goal-function structures of a plant, it also implies the component level, which allows to synthesize the identified alternative means into a sequence of human operations, i.e. operating procedures. An operating procedure can explain how to establish the desired functions that can lead to the defined goals. In the previous study [5], it has been investigated that MFM can be used to generate operating procedures for a specific goal. Below it will show how this MFM-based procedure generation method combined with the alternative identification approaches described in Section 4.1 can produce plans for an accident situation.

Figure 6 shows the flow chart of procedure generation. In step 1, the unavailable functions must be defined according to the accident situation. In step 2, a goal of counter measure should be specified for the current situation. The defined goal should be corresponded to an MFM objective in the model. In step 4, from this objective, the casual inference will be applied to derive a cause, that is, a possible state change of an available function that can influence the objective achievement. This state must be able to be controlled directly by an operation on corresponding component. Note that some independent operations can be found due to multiple inference paths. In step 6, conditions or preconditions are checked for each operation, which could be a specific state of a function or an objective. If the operation can be executed without any condition, then the procedure with only one operation is displayed. Otherwise, the conditions must be satisfied before. It is necessary to apply the causal inference again to search necessary operations for conditions. The later found operations will be added before the former one in a procedure.

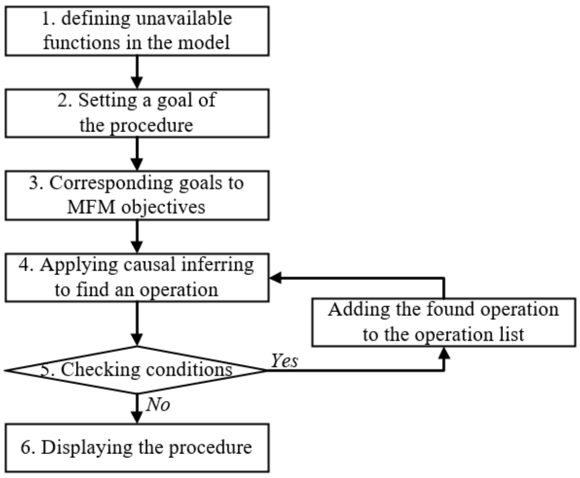


Fig. 6 Flow chart of procedure generation

Since the operations are searched from the available functions in the current situation, during this process the two approaches of identifying alternative means introduced in Section 4.1 play a significant role, the procedures generated can be treated as the available means so far to realize the specific goal of counter measure.

5 Response Planning for SBO

In this section, it will show that how to use MFM to generate alternative means in the form of operating procedure to achieve the goal of core cooling in the event of SBO, when most of systems designed for reactor injection were damaged.

5.1 Unavailable functions in SBO

The unavailable functions in SBO mainly refer to the functions of ECCS systems because of loss of on-site and off-site power facilities. Besides an independent failure is also assumed for the RCIC system in this paper which is the only injection system of BWR that is driven by steam rather than AC power. As shown in the MFM model in Figure 7, the symbols described by the dashed lines represent the unavailable functions in the event of SBO.

5.2 Formulating plans by MFM

To achieve the goal of core cooling, we specify the objective *obj6*, i.e. to maintain heat removal from the energy storage in the reactor core, as a trigger to find necessary operations. In Figure 7, one of the functional paths that can lead to objective *obj6* is highlighted in bold red, in which the desired states of functions *bar14*, *bar11*, *bar9* and *tra37* indicate operations on related component.

Therefore, a response plan can be formulated as an operating procedure by ordering these operations.

Table 2 shows all the procedures generated for the goal of core cooling. The bracket after each operation indicates the desired state of the corresponding function. Procedures 1 and 2 suggest how to apply the FP and the MUWC system to achieve the low-pressure injection. Note that for both of them, depressurizing the PRV by opening SRV is necessary. Procedures 3 and 4 also indicate the usage of above alternative water injection systems but pipelines of the other systems are applied. The last procedure shows that the single operation of opening SRV has positive effect on core cooling.

It should be noted that the level of abstraction on the component in MFM is only chosen to reflect the attention that is normally needed during operation, which means the identified procedures may not include the possible auxiliary operations attached with each operation.

6 Conclusions

The paper investigated the capability of multilevel flow modeling for supporting accident management especially for the activity of response planning. It is concluded that the plant knowledge represented by this functional modeling method can serve the basis to manage the planning related resources. Moreover, MFM can be used to identify alternative means for

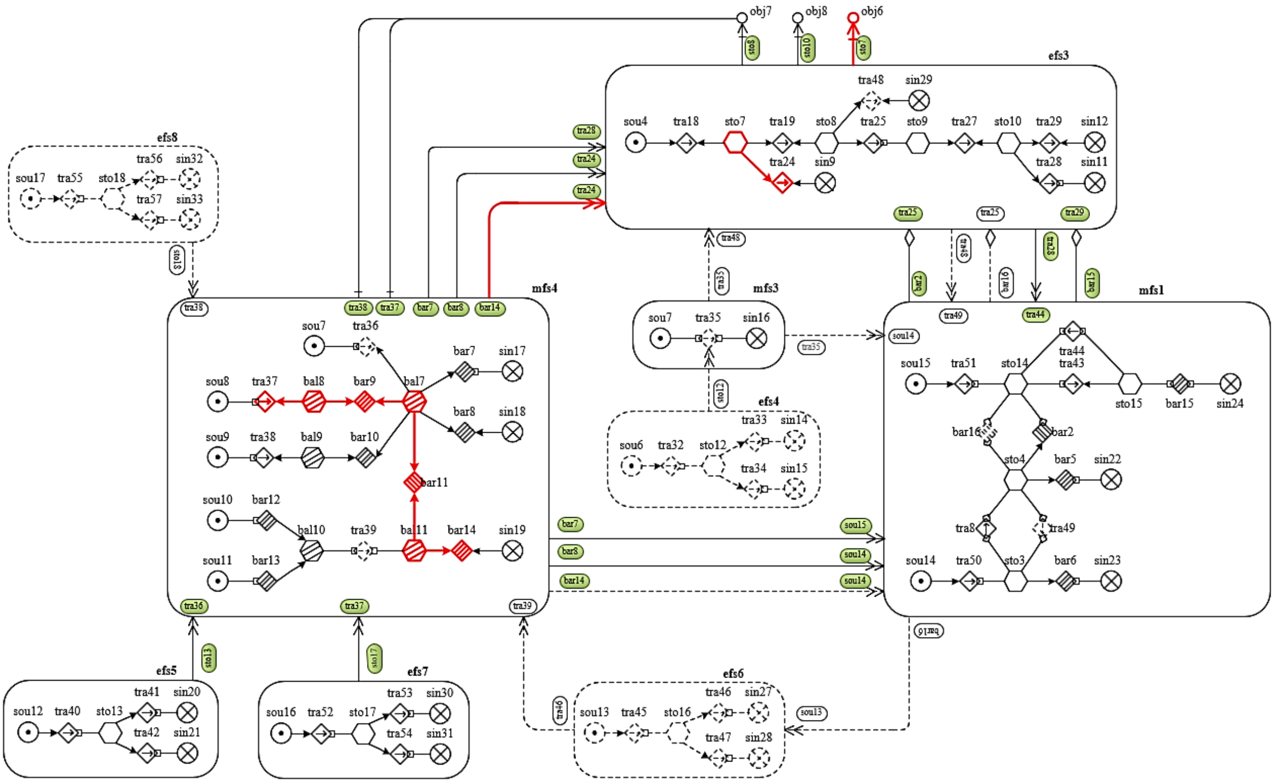


Fig.7 Available functions in SBO

achieving a goal of countermeasure, which may be beyond their original purposes considered by plant designers but have positive effects on goal achievement. Based on the previous study, the alternative means can be further expressed as operating procedure with a series of human operations. It is instructive to apply the method in the paper to deal with the unexpected situations when pre-defined countermeasures may fail. A case of station blackout of the boiling water reactor shows that multiple plans in the form of operating procedure are generated to achieve core cooling based on an MFM model, considering most of design-based means of core cooling are lost during the accident.

Nomenclature

AC	Alternating Current
BWR	Boiling Water Reactor
ECCS	Emergency Core Cooling System
EOP	Emergency Operating procedure
FP	Fire Protection System
MFM	Multilevel Flow Modeling
MUWC	Make-Up Water System (Condensate)
NPP	Nuclear Power Plant
PCV	Primary Containment Vessel
RCIC	Reactor Core Isolation Cooling System
RHR	Residual Heat Removal System
RPV	Reactor Pressure Vessel
SBO	Station Blackout
SRV	Safety Relief Valve

Table 2 Procedures identified for core cooling

Step	Procedure 1	Procedure 2	Procedure 3	Procedure 4	Procedure 5
1.	open SRV (*bar2* leak)	open SRV (*bar2* leak)	open SRV (*bar2* leak)	open SRV (*bar2* leak)	open SRV (*bar2* leak)
2.	start FP pump (*tra37* hiflo)	start condensate transfer valve (*tra38* hiflo)	start FP pump (*tra37* hiflo)	start condensate transfer valve (*tra38* hiflo)	
3.	open FP valve (*bar9* leak)	open MUWS valve (*bar10* leak)	open FP valve (*bar9* leak)	open MUWS valve (*bar10* leak)	
4.	open low-pressure injection valve (*bar8* leak)	open low-pressure injection valve (*bar8* leak)	open connection valve (*bar11* leak)	open connection valve (*bar11* leak)	
5.			open RCIC injection valve (*bar14* leak)	open RCIC injection valve (*bar14* leak)	

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