Multilevel flow modeling of Monju Nuclear Power Plant

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Abstract: Multilevel Flow Modeling is a method for modeling complex processes on multiple levels of means-end and part-whole abstraction. The modeling method has been applied on a wide range of processes including power plants, chemical engineering plants and power systems. The modeling method is supported with reasoning tools for fault diagnosis and control and is proposed to be used as a central knowledge base giving integrated support in diagnosis and maintenance tasks. Recent developments of MFM include the introduction of concepts for representation of control functions and the relations between plant functions and structure.

The paper will describe how MFM can be used to represent the goals and functions of the Japanese Monju Nuclear Power Plant. A detailed explanation will be given of the model describing the relations between levels of goal, function and structural. Furthermore, it will be explained how goals and functions of the control systems are represented using the recent MFM extensions for modeling control functions.

Keyword: Multilevel Flow Modeling; knowledge based systems; supervisory control; human-machine interface

1 Introduction

Efficient monitoring and control of energy systems and process plant is of importance for industry due to the increasing complexity and risk of operations. Current considerations in the nuclear power domain include integration of monitoring and diagnosis functions and the application of knowledge based systems for decision support in risk monitoring. Multilevel Flow Modeling (MFM) is a methodology for representation of complex plants in knowledge bases which is currently considered as a common knowledge base in monitoring and control[1]. The paper describes an application of Multilevel Flow Modeling for the Japanese fast breeder reactor prototype MONJU.

MFM is a method for modeling complex processes on multiple levels of means-end and part-whole abstraction[2,3]. MFM has been applied on a wide range of processes including power plants, chemical engineering plants and power systems. MFM is supported with reasoning tools for fault diagnosis and control[4]. Recent developments of MFM include the introduction of concepts for representation of control functions[5] and the relations between plant functions and structure[6] .

2 The MONJU Nuclear Power Plant

The MONJU Nuclear Power Plant (NPP) has a moderate electrical output of 280 MWe at full power but the plant configuration is rather complex and peculiar in comparison with a conventional light water reactor. The reactor fuel is mixed oxide pellets with stainless steel cladding, and the reactor coolant is liquid sodium. The plant is composed by three different loops. The reactor power generated in the core is transferred by sodium coolant in the primary loop. The conveyed heat in the primary loop is then transferred to a sodium coolant in the secondary loop by the intermediate heat exchanger. The heat conveyed by the secondary sodium coolant is then transferred to the water coolant in the ternary loop by a rather complex configuration of water passage route including a super-heater, steam separator, evaporator, turbine, condenser, as well as air ventilation paths and many bypass route for the steam by the manipulation of many valves.

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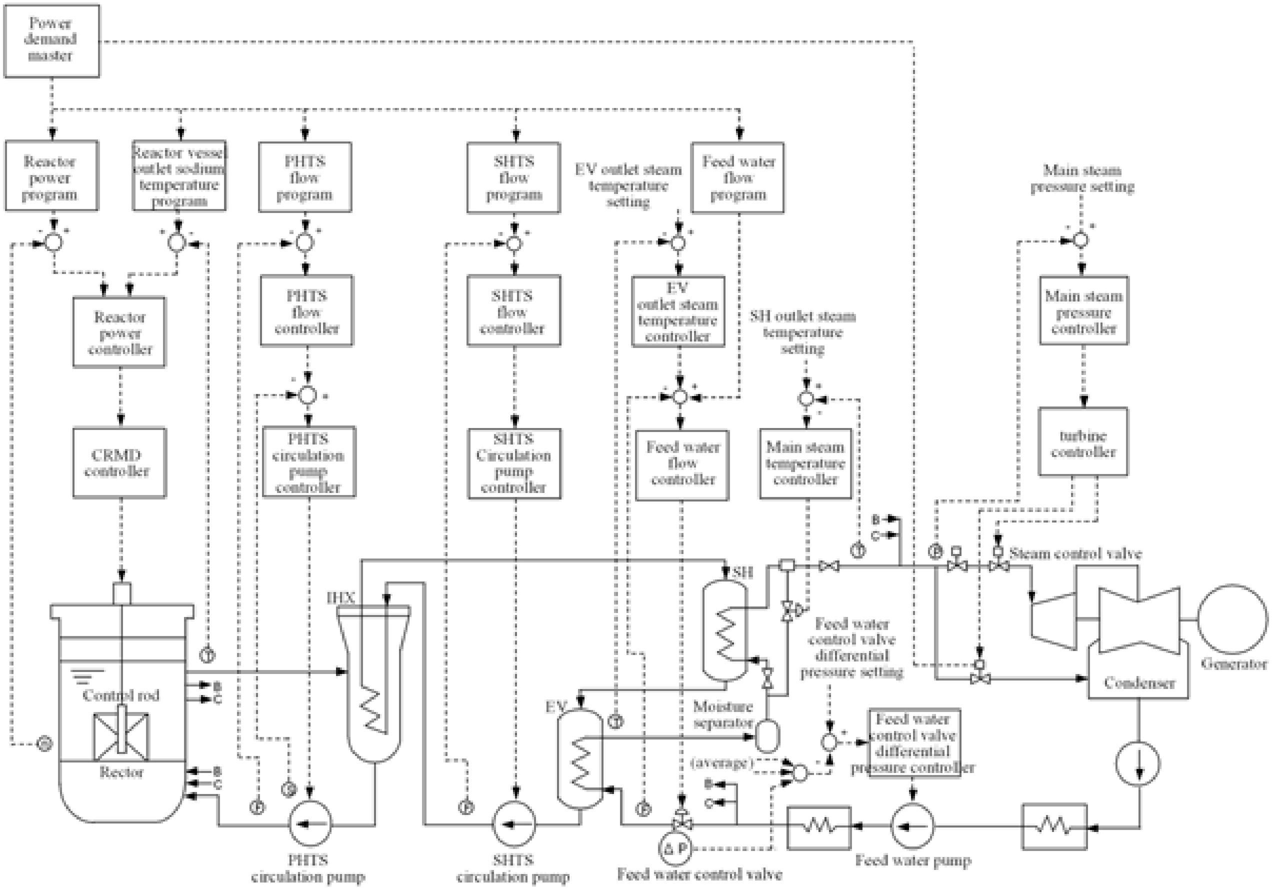


Fig. 1 The MONJU NPP and its control systems.

The P&I diagram of the Monju FBR shown in Fig. 1 is therefore more complex than for a light water reactor due to the many loops, components, pipes and valves, *etc*. and many feedback control systems. Details of the control system of the MONJU plant are described by Takahashi and Tamayama[7]. The MONJU plant stopped operation in December, 1995 due to a sodium leak accident in and was restarted in May 6, 2010.

3 Multilevel Flow Modeling

MFM belong to the branch of AI research called qualitative reasoning. The purpose of this research is to represent and reason about qualitative knowledge of physical phenomena and systems which cannot be done by quantitative approaches based on first principles such as differential equations. The MFM modeling language realize these aims within the general domain of industrial processes and their automation systems. A particular challenge addressed by MFM is to offer modeling and reasoning techniques that can handle the complexity of large scale dynamic processes.

MFM represent goals and functions of process plants involving interactions between flows of material, energy and information. Concepts of means-end and whole-part decomposition and aggregation play a foundational role in MFM. These concepts enable humans to cope with complexity because they facilitate reasoning on different levels of abstraction. The power of means-end and part-whole concepts in dealing with complexity has roots in natural language. But natural language is not efficient for representing and reasoning about means-end and part-whole abstractions of complex physical artifacts. MFM development draws on insights from the semantic structure of natural language but is designed as an artificial diagrammatic language which can serve modeling needs of complex engineering domains. MFM concepts and their graphic representations are shown in Fig. 2. A detailed introduction to MFM and description of modeling examples are presented elsewhere[3]. MFM concepts are introduced below by a simple heat transfer loop example (Fig. 3) which presents the basic features of MFM and functions which are generic to heat transfer loops.

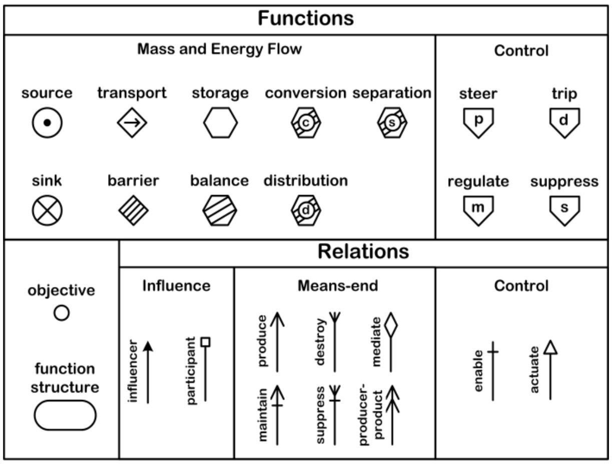


Fig. 2 MFM concepts and symbols[3].

The MFM of the heat transfer loop can be used as a template when modeling the MONJU plant since this plant contains several interacting heat transfer loops. The heat transfer loop example will accordingly make it easier to understand the MONJU model and reduce the need for a detailed description of the complete model shown in Fig. 4.

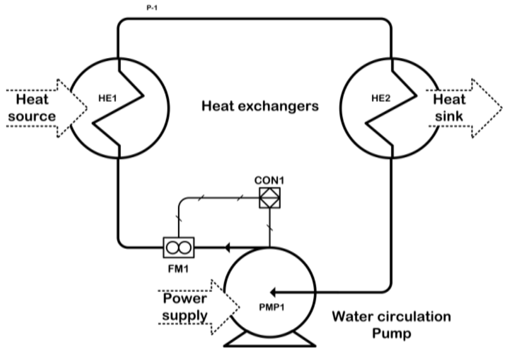


Fig. 3 A heat transfer loop example.

3.1 The heat transfer loop

The heat transfer loop in Fig. 3 comprises two heat exchangers HE1 and HE2 connected by a circulation loop including a pump PMP1. The type of fluid used for heat transfer has no significance for the MFM but we will assume for convenience that it is water. We will also ignore physical details which are not relevant for the purpose of the paper. This includes also physical details of the power supply for the pump

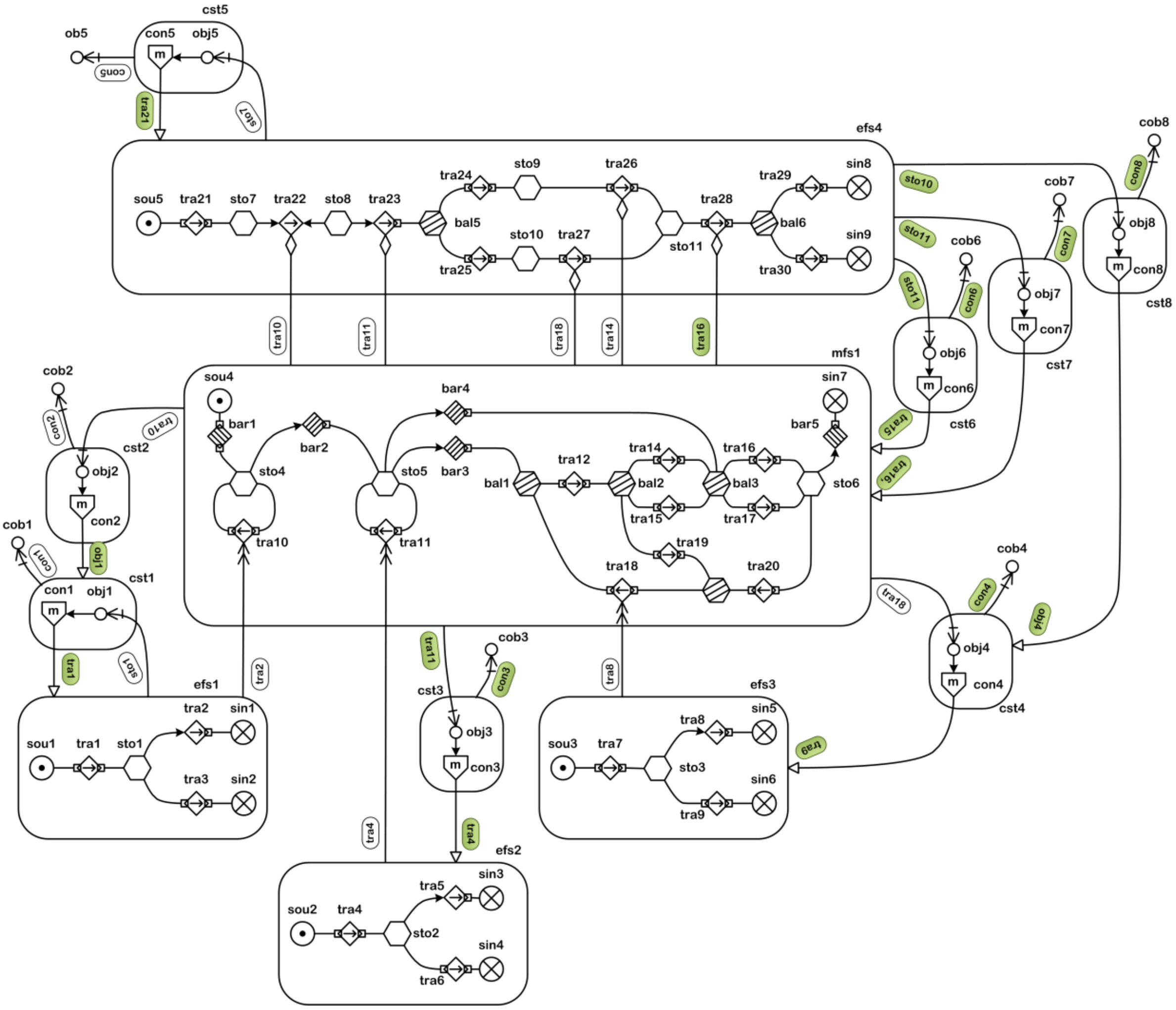


Fig. 4 MFM model of the MONJU nuclear power plant.

motor and of the systems serving as energy sources and sinks. The water flow rate in the circulation loop is maintained by the controller CON1 on the basis of readings obtained from a flow measuring device (FM1). We will present a model of the heat transfer loop without control systems and a model including the control system.

3.1.1 MFM of heat transfer loop without control

Figure 5 shows the MFM of the heat transfer loop without control. It contains three functional levels comprising an energy flow structure efs1, a mass flow structure mfs1 and an energy flow structure efs2. We will explain the model from bottom to top.

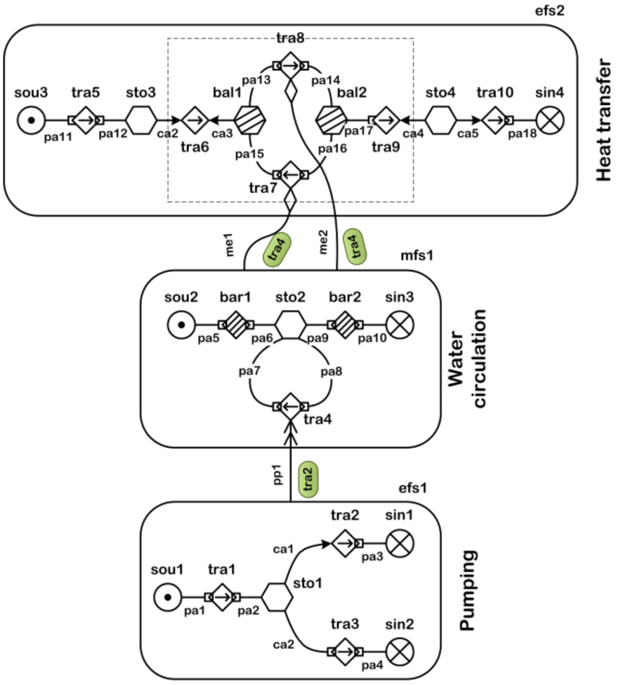


Fig. 5 MFM of the heat transfer loop without control.

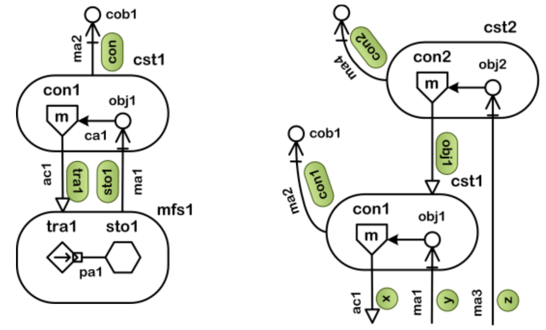
The energy flow structure efs1 represents the functions involved in pumping of the water in the circulation loop when seen as an energy conversion process. The source sou1 represents the power supply, sto1 the accumulation of rotational and translational energy in the hydraulic circuit and tra2 and tra3 represents conversion of the rotational energy into kinetic energy of the water (tra2 and sin1) and friction losses in the circulation loop (tra3 and sin2).

Mass flow structure mfs1 represents the functions of the water circulation loop. The function tra4 represents the transportation of water resulting from the energy conversion in the pump represented by efs1. It is connected with efs1 by a producer-product relation pp1 which is a means-end relation. The relation pp1 is labeled with the name of the function in efs1 which is directly associated with tra4 namely tra2 (the main function of the pp1 relation[3]. Since the water is re-circulated the two ends of the transport function tra4 are connected with the function sto2 representing the storage of water in the circuit. The storage sto2 is also connected with two barriers bar1 and bar2. They represent the prevention of material flows to enter (sou2 and bar1) or leave (bar2 and sin3) the circulation loop provided by the piping walls in the heat exchangers HE1 and HE2.

We now continue to efs2 which represents the heat transfer functions. The water circulation loop is here seen in the context of the systems serving as a heat source and a sink. The function of the loop is in this context to transport energy from the outlet of HE1 (tra7) to the inlet of HE2 (tra8) and to transport from outlet of HE2 to the inlet of HE1 (tra7). Since the transportation of energy represented by tra7 and tra8 both are mediated by the circulating water, tra7 and tra8 are connected with mfs1 by two mediation relations me1 and me2. The mediation relations are both labeled by tra4 which is the main function in mfs1. The heat transfer from the source (sou3) to the primary side of HE1 is represented by tra5 and sto3. The transfer from the heat storage in the HE1 primary to the circulation loop is represented by tra6 and bal1 which is connected with the incoming and outgoing energy flows (tra7 and tra8). The heat transfer and storage in HE2 are represented in a similar way by functions bal2, tra9 and sto4. The heat transfer from the secondary side of HE2 to the sink is represented by tra10 and sin4.

3.1.2 Representation of control functions

Before presenting a model of the heat transfer loop including the control system we will explain how MFM represent control functions[5]. The basic principle is shown in Fig. 6(a) where we have a simple mass flow structure containing only two functions namely a transport (tra1) and a storage (sto1). The storage could represent the function of a water tank and tra1 could represent the function of an inlet pipe with a control valve. The flow structure is incomplete according to the syntax of MFM but is suitable for the present discussion. A syntactically correct model would include additional functions which would be irrelevant here.



(a) Simple control loop (example)

(b) Control cascade

Fig. 6 Control functions in MFM.

The function of a controller maintaining the water level in the tank is represented by the control structure cst1 in Fig. 6(a). The regulation function of the controller is represented by con1 and the set-point value for the water level is represented by the objective obj1. The objective is obviously related to the state of the storage function sto1 and it is therefore connected with mfs1 by a maintain relation ma1 (with label sto1). The control function is connected with mfs1 by an actuation relation ac1. This relation points via its label to the function in mfs1 which is actuated by the control function (tra1).

Note that the inlet pipe and the control valve therefore have two functions, to transport the inlet water and to serve as a means for control. Finally, the control structure cst1 is connected with the objective cob1 through a maintain relation ma2. The control objective cob1 define a norm for the controller performance and should be clearly distinguished from the plant objective obj1 which represents a norm for the process performance.

Control cascades can be represented by MFM following the same principles as for a single loop as shown in Fig. 6(b). The cascade includes here two control functions con1 and con2 where con2 determine the objective of con1 via the actuation relation ac2.

Note that MFM represents control systems by their purpose. Models of control systems in MFM are therefore process centric *i.e.* expressed in terms of the process and not in terms of the control algorithms or information processes used for their implementation.

3.1.3 MFM of the heat transfer loop with control

When these principles for representing control functions are applied to the heat transfer loop we obtain the model shown in Fig. 7. The controller is here assumed to use the power supplied to the pump (tra1) to control the pump speed (sto1) so that the water flow rate (tra4) can be maintained at its desired value (obj1).

Note that efs2 in Fig. 6 is simplified compared with efs2 in Fig.5 by aggregating the encircled sub-structure in Fig. 5 into tra11 in Fig. 6. MFM allow such aggregations.

The modeling example shows that control functions may include several functional levels (efs1 and mfs1 in Fig. 7). This is also exemplified in the MFM of MONJU.

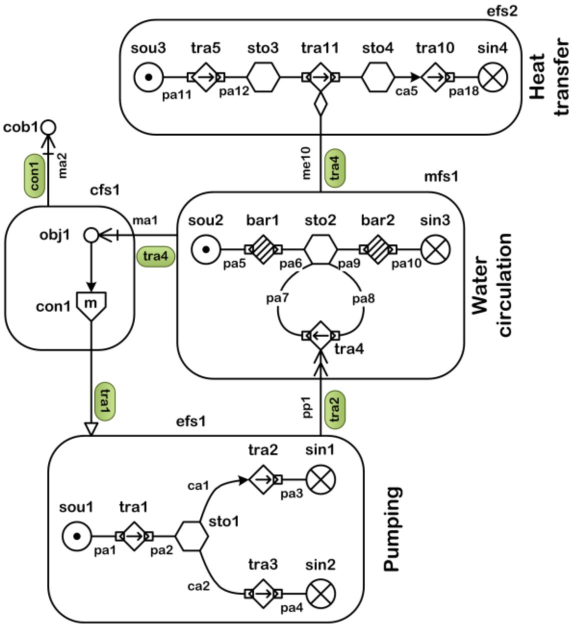


Fig. 7 MFM of the heat transfer loop with control. Note that tra11 is an aggregation of the functions in the dotted rectangle in Fig. 5.

4 MFM of the MONJU NPP

We will now explain the MFM of MONJU and its control systems which are shown by the P&I diagram in Fig. 1. P&I diagrams are understood by process and control engineers but the information expressed in an MFM model cannot be extracted from a P&I diagram because it does not contain information about goals and functions in an explicit form. Often engineers claim that P&I diagrams are sufficient because they know about the goals and functions and can relate to it in their minds when they read the diagrams. However, the advantage of making this knowledge explicit as done by MFM is obvious because it can be used in the process and automation design or for building knowledge based decision support system for the operators.

We will build the MFM model of MONJU by decomposing the plant into the following three subsystems

- Primary heat transfer system (PHTS)
- Secondary heat transfer system (SHTS)
- Energy conversion system (ECS)

Each subsystem and the included components will be defined below.

Note that this decomposition into *systems* is reflected neither in the P&I diagram nor in the MFM model. The P&I decompose into components or equipment and MFM decompose into levels of function. Functions and components are related by many to many mappings *i.e.* models of functions and components are not isomorphic. A decomposition of the plant into components accordingly cannot address functional constraints (and the reverse).

By decomposing MONJU into the three subsystems suggested above we can use the heat transfer loop MFM described above (Fig. 7) as a template for modeling the PHTS and the SHTS subsystems. But since the subsystems do not strictly match the functional decomposition of MFM we need to apply “partial” or incomplete function structures when representing subsystem functions. Incompleteness of a function structure will be indicated by using a dotted line in its graphical representation. However, even though the function structures for the PHTS systems, the SHTS system and ECS are incomplete they can be directly combined into the “complete” function structures of MONJU shown in Fig. 4. In order to indicate how the subsystem models are integrated in the complete model in Fig. 4 we will for each subsystem model include “interface” functions belonging to other functionally related subsystems.

Note that the overall coordination functions of the control loops in MONJU performed by the power demand master, the reactor power program, the reactor outlet sodium temperature program, the PHTS flow program, the STHTS flow program and the feed water flow program are not included in the MFM model of MONJU presented in this paper.

4.1 Primary heat transfer system PHTS

The components in the primary heat transfer system PHTS includes the reactor with control rods, the CRMD controller, the reactor power controller, the sodium coolant, the IHX heat exchanger, the PHTS circulation pump, the PHTS circulation pump controller and the PHTS flow controller. The MFM of PHTS system is shown in Fig. 8. The PHTS model contains like the heat transfer loop model in Fig. 7 three functional levels efs1, mfs1 and efs4 and share also some other more detailed features.

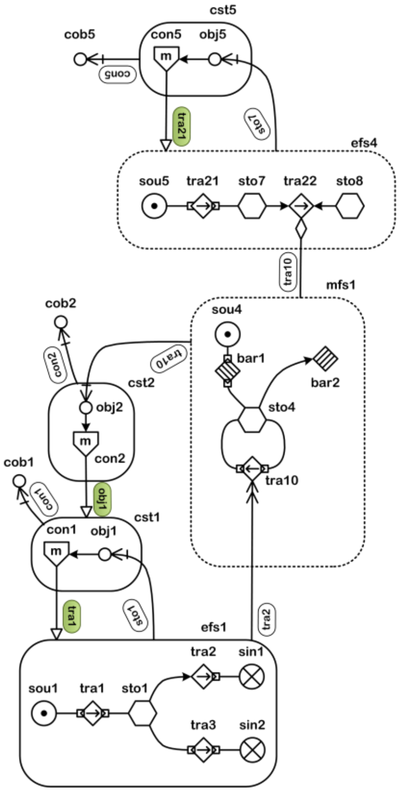


Fig. 8 MFM of the PHTS system.

The functions within function structure efs1 represent the pumping and hydraulic functions of the PHST involved in the conversion of electrical energy to rotational and kinetic energy in the hydraulic circuit.

The structure mfs1 represents the storage (sto4) of sodium in the core and its circular transportation (tra10) and is therefore in this respect identical to similar functions of the heat transfer loop example. Thus, it includes the producer-product relation connecting the transport function tra10 with the means of transport represented by the pumping functions within efs1. The structure mfs1 includes also a source sou4 representing the radioactive material in the core and two barrier functions bar1 and bar2. The barrier bar1 represents the function of the cladding which in this context is to prevent the radioactive material from leaving the fuel elements. The barrier bar2 represents a function of the IHX heat exchanger which is to separate the primary and the secondary coolant media so that radioactive materials which potentially may be contained by the PHTS coolant is prevented from entering the SHTS system.

The structure efs4 represents the delivery (sou5), transfer (tra21) and storage (sto7) of energy in the reactor coolant circuit. The transfer of energy from the PHTS to the SHTS mediated by the circulation of coolant is represented by tra22 including its connection with tra10 in mfs1 by a mediation relation. Storage sto8 represents a function of the SHTS system which will be discussed below.

4.1.1 The PHTS control loops

The PHTS includes three control loops whose functions are also represented Fig. 8. They are all based on the principles for representation of control functions described above.

We will first explain the representation of the functions of the PHTS circulation pump controller and the PHTS flow controller. These two controllers are connected in a cascade because the set-point for the circulation pump controller is the output of the flow controller. We have therefore applied the principles for MFM modelling of control cascades described above.

The functions of the circulation pump controller is represented by cst1. The purpose of this controller is to maintain pump speed at its set-point and its objective obj1 is therefore related to the accumulated rotational energy in the pump (sto1). The speed is kept constant by regulating the power delivered (tra1) to the pump. The actuation relation connects therefore the control function con1 with tra1 in mfs1 in the MFM model.

The purpose of the PHST flow controller is to maintain the flow rate of the sodium coolant at its set-point value. This is repesented in the MFM model by the control function con2. Its objective obj2 is therefore related to the transport function tra10. The flow rate is maintained by regulating the set-point (obj1) to the PHTS flow controller and con2 is therefore connected with obj1 by an actuation relation.

Finally we will consider the combined function of the CRMD controller and the reactor power controller in MONJU. The control function is simply represented by con5 in the PHTS MFM model in Fig. 8. But explaining how control rods are represented requires a little more effort. As is well known, the purpose of the rods is to control the nuclear reactions in the core by absorbing neutrons. In functional terms this means that the rods serve as an actuator which can change the amount of energy transferred from the fuel to the coolant. We have therefore represented the control rods by means of the actuation relation connecting the control function con5 with the energy transport function tra21 in efs4. The objective obj5 represents the set-point (power level and temperature) for the reactor power controller and is therefore associated by a maintain relation with sto7.

4.2 Secondary heat transfer system SHTS

The components in the SHTS subsystem include the IHX heat exchanger, the SHTS circulation pump, the evaporator EV and the superheater SH. Note that the IHX is also part of the PHTS system and that the EV and SH are also part of the ECS. This reflects the problems of decomposition mentioned above.

The main purpose of the SHTS system is to transfer energy from the PHTS system to the energy conversion system. The MFM of SHTS system is shown in Fig. 9. It has many similarities with the heat exchange loop example in Fig. 7 both with regard to the functional structures efs4, mfs1 and efs2 and the functions they include. The control structures are actually identical. We will therefore only explain the differences between the models in Figs. 7 and 9 which can be found in function structure mfs1 and efs4.

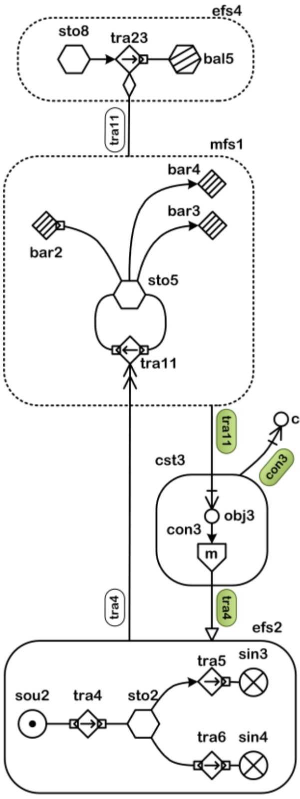


Fig. 9 MFM of the SHTS system.

With regard to mfs1 the only difference is that the SHTS model includes three barrier functions bar2 and bar3 and bar4. These three barriers represent safety functions of the SHTS which is to prevent the transfer of radioactive material between the PHTS and the ECS (through the evaporator EV and the super-heater SH).

In function structure efs4 representing the energy transfer function (tra23) of the SHTS system we have included a storage (sto8) representing the storage of heat in the coolant and the components in the SHTS circuit. The balance bal5 is an interface to the ECS model described below and is there used to represent the split of the energy transferred into two energy flow paths one related to the evaporator (EV) and the other to the super heater SH.

4.3 Energy conversion system

The main components of the energy conversion system includes the evaporator EV, the super heater SH, the moisture separator, the feed water pump, the turbine generator and the condenser and the condensate pump. The functions of these components are highly interacting and the MFM of the ECS shown in Fig. 10 is by far the most complex of the three sub-models considered here.

Figure 10 shows the functions of the ECS which should be included in efs4 and mfs1 together with the functions shared by the PHTS and the SHTS systems as already described. We will explain the ECS functions in efs4 and mfs1 in detail below after describing the ECS functions included in efs3 and the associated control structure cst4.

4.3.1 The functions of the ECS in efs3 and cst4

The functions in efs3 and cst4 require less explanation due to the similarity with efs2 and cst3 describing the functions of the SHTS pump and its associated control. The energy aspects of the pumping are represented by efs3. The power supply to the feed water pump is represented by sou3, the energy conversion to kinetic energy of the feed water is represented by tra8 and by tra9 which represents the losses due to pressure drops in the circuit including the pressure drop caused by the feed water control valve. Since the feed water is controlled by changing the pressure drop across the control valve, the control function con4 in cst4 is actuating tra9 (instead of tra7 which would be the case if the electric power was used to change pump speed as in the SHTS).

The feed water controller is part of a cascade involving a temperature controller represented by cst8. The objective of this controller is related to the energy storage in the evaporator EV which is represented in efs4 by the storage function sto10. It is realized that his cascade includes the interaction of three functional levels.

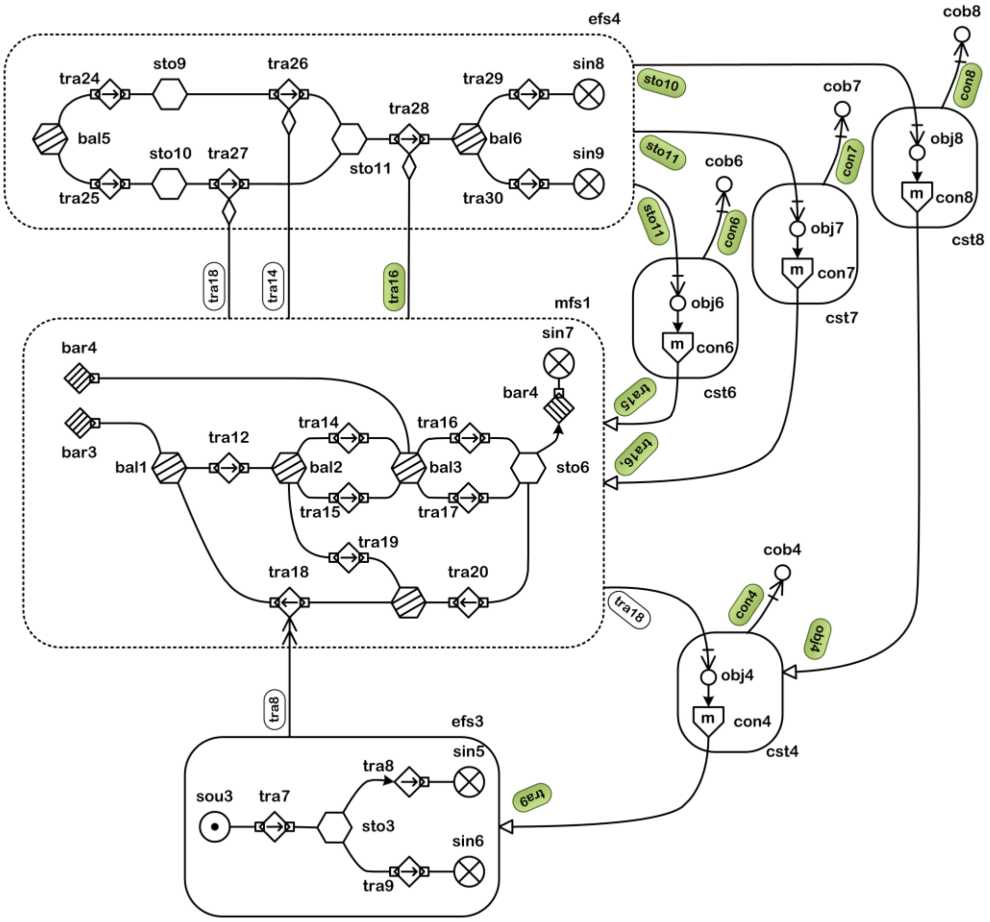


Fig. 10 MFM of the energy conversion system.

4.3.2 The functions of the ECS in mfs1

We will now consider the mass flow structure mfs1 in more detail. A natural place to start is at the transport function tra18 which represents the transportation of feed water caused by the pumping whose functions we have described above. The balance bal1 located upstream tra18 represents the balancing of the feed flow with the output flow (tra12) to the moisture separator performed by the evaporator (EV). The separation is represented by the balance function bal2 and the three transport functions tra19, tra14 and tra15. The water separated from the steam (tra19) is returned to the main feed water line. This is represented by bal4 which combines the flow from the condenser pump (tra20) with the separated water (tra19).

Now go back to the separator and its representation by bal2 and the associated transport functions tra14 and tra15. These two transport functions represent the two flow paths for steam leading to the turbine. The transportation of superheated steam produced by SH is represented by tra14 and is used for control (see below). The transport tra15 represent the transportation of steam from the evaporator output directly to the point (bal3) where it is mixed with the superheated steam. From bal3 there are two flow paths represented by tra16 and tra17. These functions represent the turbine (tra16) and the bypass line to the condenser whose function is represented by sto6 since its purpose is to collect the water condensed by the turbine and the bypass flow.

The function structure mfs1 also includes three barriers bar3, bar4 and bar5 representing safety functions of the evaporator, the super heater and the condenser. The three barriers are provided in order to prevent transportation of radioactive materials into the water steam cycle and to the environment via the condenser.

4.3.3 The functions of the ECS in efs4

We will start the description of the ECS function in efs4 at bal5 which represents the aggregated function of the SHTS side of the evaporator EV and the super-heater SH. The two energy transport functions tra24 and tra25 represent the energy transferred from the SHTS to the secondary sides of the evaporator (tra25) and the super-heater (tra24). The energy accumulation in the evaporator and super-heater are represented by sto9 and sto19 and tra26 and tra27 represent the energy transfers from the EV and the SH to the turbine by the steam. The conversion of energy in the turbine-generator is represented by tra28, bal6, tra29 and tra30. Transport tra29 represents here the transfer of the electric energy generated by the generator to the grid represented by the sink function sin8. Transport tra30 represents the transfer of energy to the condenser which here for simplicity is represented as sin9. A more complete model would represent the condenser as a storage function and include the recirculation to the feed-water system. An MFM model representing the functions of the water steam cycle in a nuclear power plant in more detail is presented by Gola *et.al.*[8].

Finally we will explain the control functions related to efs4. We have here three control structures representing the functions of the EV outlet temperature controller (cst8) and the main steam temperature control system (cst6 and cst7) which regulate the ratio between the steam flows produced by the EV and the SH. Note that the main steam pressure control and the turbine controller are not included in the model.

4.4 MFM of the MONJU system

The complete model shown in Fig. 4 can be constructed by combining the three MFM models of the PHTS, SHTS and the ECS systems.

5 Discussion

It should be noted that the MFM model developed above represent goals and functions of the Monju nuclear power plant under normal operation. It can accordingly be applied *e.g.* to diagnose deviations from normal operation but is not valid for situations where modeling assumptions are not satisfied. This may happen in certain accidents scenarios (*e.g.* steam generator tube rupture). MFM models for such scenarios are under development as part of the more general problem of modelling different plant operating modes. An MFM model covering the whole operational range of a plant (including design basis accidents) would typically consist of several (interrelated) models. Ongoing research investigate this modelling challenge.

The control functions included in the MONJU model were restricted to control functions not related to safety. Lind[9] present basic concepts for modeling safety functions of control systems. Further development of these concepts for modeling safety is ongoing and is seen in context of the problem of modeling operating modes mentioned above.

The control functions in the MONJU models were single input single output controllers. The extension and application of MFM for modelling multivariable controls are considered by Heussen and Lind[10] in relation to MFM modeling of power systems.

6 Conclusions

The paper has presented a model of the MONJU nuclear power plant. The model was developed by using a generic MFM model of a heat transfer loop to model and combine the functions of three major subssystems of the MONJU plant. It was shown that the principles for representing control system functions can be successfully applied for a complex system like the MONJU. The model presented is the first modelling example for nuclear power plants focussing om the representation of control system. Other MFM models of NPP’s have been developed. The model presented by Gola *et. al.* of the Finnish Loviisa NPP does not focus on representation of the control systems but provides on the other hand a more detailed model of the water steam cycle.

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References

[1] YOSHIKAWA, H., YANG, M., LIND, M.,TAMAYA, K and OKUSA, K.: Development of Semiotic Framework of Proactive Trouble prevention Knowledge Base System and it Application for FBR Prototype Plant Monju,

Proceedings of 7'th American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and HMI Technologies NPIC&HMIT 2010. Las Vegas, Nevada, November 7-11.

[2] LIND, M.: Modeling Goals and Functions of Complex Industrial Plant, Applied Artificial Intelligence, 1994, 8(2): 259-283.

[3] LIND, M.: Introduction to Multilevel Flow Modeling, Journal of Nuclear Safety and Simulation, 2011, 2(1):22-32.

[4] LIND, M.: Reasoning about Causes and Consequences in Multilevel Flow Models, Proc. European Safety and Reliability Conference (ESREL) 2011 Annual Conference, 2011, September 18-22, Troyes, France.

[5] LIND, M.: A Goal-Function Approach to Analysis of Control Situations, Proc. 11’th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Human-Machine Systems, Valenciennes, France, 31August – 3 September, 2010.

[6] LIND, M. Knowledge Representation for Integrated Plant Operation and Maintenance, Proc. 7'th American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT 2010, Las Vegas, Nevada, November 7-11.

[7] TAKAHASHI, H., and TAMAYAMA, K.: Practice of Operation and Control of Fast Reactor, Chapter 5, Part I Practice of Nuclear Power Plant Control, In: Reactor Dynamic Control and Plant Control, Ed: by Yoshiaki Oka and Katsuo Suzuki, Ohmsha, Tokyo, Japan, 2008: 165-187 (In Japanese).

[8] GOLA, G., LIND, M., THUNEM, H., and THUNEM, A.: Multilevel Flow Modeling for Nuclear Power Plant Diagnostics, Proc. European Safety and Reliability Conference (ESREL) 2011 Annual Conference, September 18-22, 2011, Troyes France.

[9] LIND, M.: Modeling Goals and Functions of Control and Safety Systems: Theoretical Foundation and extensions of MFM. Tech Report from NKS-R-07 project, 2005.

[10] HEUSSEN, K., and LIND, M.: Representing Causality and Reasoning about Controllability of Multi-level Flow-Systems, Proc 2010 IEEE Conference on Systems, Man and Cybernetics, Istanbul, Turkey, 2010.