Reasoning about Cause-effect through Control Functions in Multilevel Flow Modelling

Xinxin ZHANG[1] and Morten LIND[2]

1. Department of Electrical Engineering, Technical University of Denmark, Elektrovej Building 326, Kgs. Lyngby 2800, Denmark (xinz@elektro.dtu.dk)
2. Department of Electrical Engineering, Technical University of Denmark, Elektrovej Building 326, Kgs. Lyngby 2800, Denmark (E-mail: mli@elektro.dtu.dk)

Abstract: Multilevel Flow Modelling has been used for modelling complex system such as nuclear power plants. The causal reasoning capability of the MFM models is explained in various literatures by the authors as well as other researchers. MFM is also used to represent control functions in relation with system objectives. This paper clarify the fulfilment of MFM objectives and extend the MFM causal reasoning rules to the control functions and use reasoning rules to generate explanations for understanding control actions. A case study based on a previous developed PWR model is used to illustrate the new reasoning rules. This work contribute to support human operators to understand system automation under abnormal situations.
Keyword: Multilevel flow modelling, causal reasoning, automation awareness

1 Introduction

Since automation is increasing in various industrial domains, many studies of human-machine interaction have focused on examining the levels of automation, function allocations between humans and machines, and their impacts on operator performances [1].

As the automation shifts human operator's role from manual to supervisory control, detecting the requirements for manual intervention and understanding automation failures becomes a big challenge when the system is poorly designed or inadequately represented to the operator. Human out-of-loop performance problems have long been identified across many industrial domains as one of the major negative effects when introducing high level of automation without carefully design the human automation interaction [2].

As a functional modelling approach, Multilevel Flow Modelling (MFM) has been used for representing complex systems such as nuclear power plants. It offers a unified representation of process and automation system at the functional level, providing causal connections between physical system and system's functions and goals. One of the advantages of using MFM models is that the MFM methodology systematically defines three categories of causality based on 1) process principle, 2) means-end relations, and 3) system control functions respectively. These three types of causality are distinctively modeled and organized together in a semantically meaningful structure that can be used for causal reasoning.

Using MFM models to reason about cause-effect based on process functions and MFM means-end relations has been introduced in prior work [3]. This paper proposes a reasoning mechanism for analyzing the cause-effects based on MFM control actions and relations. The reasoning result of control influences based on MFM models can be combined with the process functions' causal dependencies to explain why a certain control function is triggered and in its relation, what control actions is programmed to deploy, and how the control actions will compensate for the process deviations.

This analysis has the potential to support human operator in understanding automatic control actions in the context of the plant state, thus contribute to enhance the automation awareness of human operators during plant operation. The reasoning rules is formulated and implemented in the MFM software tool and the preliminary result is demonstrated by using a generic PWR system as a case study.

2 Control functions in MFM

Lind [4] derived the theoretical foundation for the control functions in MFM from the work of Von Wright by a semantic analysis of his action types.

The control functions in MFM describe the control intention and the control relations describe the mapping of the system's control intentions to the means of actuation on the functional level.

Table 1 shows the four types of control functions in MFM terminology that was introduced in [4]. The arrows link the state p/~p and the MFM control functions indicate the influence relations between them, where the fulfilment of states of the objectives influence the control functions to deploy the control actuations.

Table 1 MFM control functions from [4]

Task	Symbol	Purpose of control
Steering	p ← p	Ensure that p is produced
Regulation	m ← p	Ensure that p is maintained
Tripping	p ← ~p	Ensure that ~p is produced
Interlocking	m ← ~p	Ensure that ~p is maintained

Following the development of MFM methodology in relation with safety barrier analysis [5], it has been determined that the logical statements of p and ~p have significant distinction in the context of plant operation. In process industries where MFM is applied, the desired process state are often separated from the undesired safety threat, where the former is commonly insured by the normal control functions while the later is prevented by safety functions. For this reason, they are treated as different functional concepts semantically in MFM.

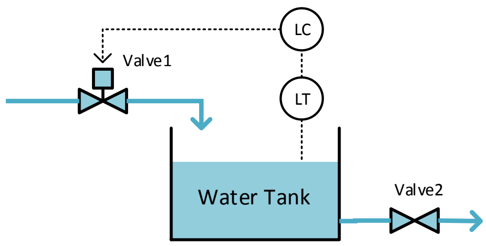
Based on this extensions and development in MFM terminology, a desirable state in the process plant is defined as a target, while an undesirable state in the process plant has been defined as a threat.

Table 2 provide the new symbols for MFM control patterns and their corresponding purposes. Each of these control patterns can form a control flow structure in MFM model. The control flow structure is connected to MFM mass and energy flow structure through means-end relation at the side of controlled states and through actuation relation at the side of the control function.

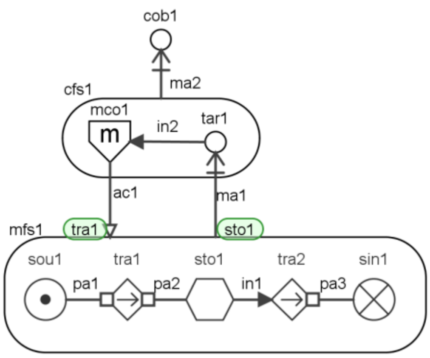
Table 2 MFM control functions

Task	Symbol	Purpose of control
Steering	p ← tar	Ensure the target state is produced
Regulation	m ← tar	Ensure the target state is maintained
Tripping	d ← thr	Ensure the threat is destroyed
Interlocking	s ← thr	Ensure the threat is suppressed

An example of a MFM control flow structure is exemplified in Fig. 1 as cfs1. The MFM model shown in Fig. 1(b) represents the controlled physical system shown in Fig. 1(a). In the physical system, the water level in the water tank is regulated through a controller. In the MFM model, the state of the material storage sto1 is directly linked to the target state tar1. The objective of the system is to maintain tar1. The state of the fulfillment of tar1 influences the control function mco1 to act upon the actuated transport function tra1. In this case, any deviation that affects the state of the storage function will propagate to tra1 due to the control. The control flow structure has its own objective, which is to maintain the state of the control performance (maintain cob1).



(a) Physical system

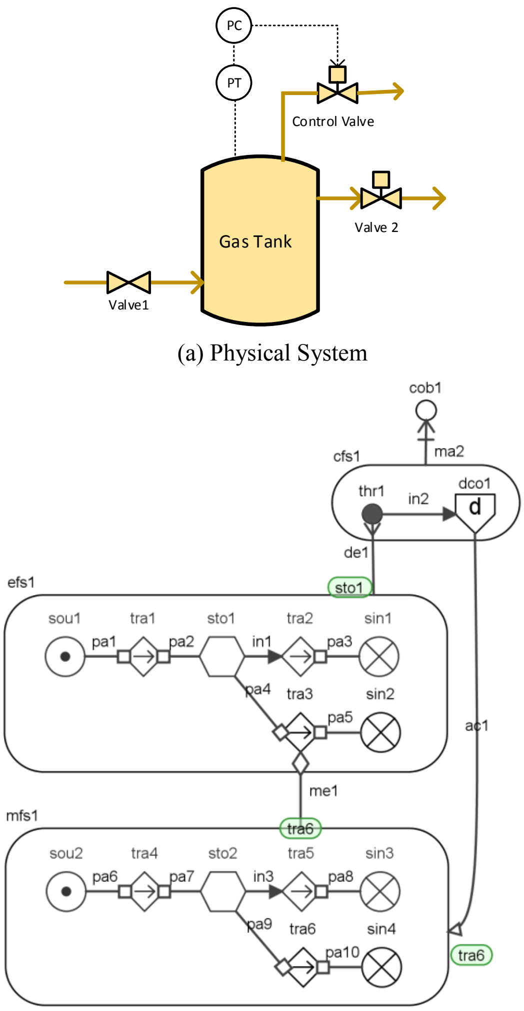


(b) MFM model

Fig. 1 Example of modelling using MFM control flow structure for water level regulation.

Another example of a safety oriented control function is shown in Fig. 2. The physical system in Fig. 2(a) shows a pressurized container with a control valve provided to avoid a high-pressure situation.

In this case, when the pressure exceeds the safety level, the control valve will act as a pressure relief valve and open by the controller to destroy a high pressure state. In the MFM model shown in Fig. 2(b), sto1 in the energy flow structure efs1 represents the accumulated pressure in the tank. The transport function tra2 in efs1 represent the energy release through the control valve. The material flow structure mfs1 represents the storing (and releasing) of the gas which serve as the means for storing (and releasing) of the energy.



(a) Physical System

(b) MFM model

Fig. 2 Example of modelling using MFM control flow structure for pressure relief valve.

In the physical system, the control function is used to destroy an undesired high state (a threat). The threat thr1 in the MFM model is linked to the state of sto1 through a destroy relation and the state of thr1 influence the controller to act upon the actuated function tra6 (function of the control valve) in mfs1, which is to release gas in order to release the pressure. The high state deviation in sto1 will propagate to tra6 in the material level due to the control.

To summarize this section, all the control related MFM concepts is listed in Table 3.

Table 3 MFM control related concepts and symbols.

Type	Name	Symbol	Type	Name	Symbol
control function	Produce	p	means-end relation	Produce	main
	Maintain	m		Maintain	main
	Destroy	d		Destroy	main
	Suppress	s		Suppress	main
objective state	Target	tar	control relation	Actuate	target
	Threat	thr			

According to MFM syntax, all the means-end relations are connected to a mass or energy flow structure with a specified main function (e.g. in Fig.2, sto1 in efs1 is the main function for destroy relation de1); and all the control relations are connected to a mass or energy flow structure with a specified target (actuated) function (e.g. in Fig.2, tra6 in mfs1 is the actuated function for actuate relation ac1). These main functions and actuated functions are noted in the green bubble associated with each relation in the graphical model.

3 Causal reasoning through MFM control functions

3.1 Deviations that influence the system objectives

To reason about causal influences through the control function, the state of the process objective need to be examined first.

From the two examples presented in Section 2, the readers may notice that the criteria for the system objective to fail are different. For example, to fulfil the system objective of maintaining a function performance, the desired state must not go beyond the normal range, which means either a high value or a low value will be considered as a failure state. On the other hand, the failure for producing a desired state is only associated with a low value (the desired state was not produced).

Following this consideration, the safety systems that implemented to deal with threats are normally different because the threats are related to a high state or a low state. This means that for any given threat in a MFM model, it has to be specified that whether the threat is related to a high state or a low state, so that the MFM model can represent the objective properly.
The target in the MFM models however, do not need this distinction, because as above mentioned, it always related to the desirable function state.

Based on this semantic meanings of MFM objectives, the failure states for threats and targets are illustrated in Table 4.

Table 4 objective failures in MFM terminology

Objective failure	target / threat state	main function state
fail to maintain a target	false	low, high, low-low, high-high
fail to produce a target	false	low, low-low
fail to suppress or destroy a high state threat	true	high-high
fail to suppress or destroy a low state threat	true	low-low

3.2 Causal rules through MFM control functions

The function of a common controller implemented in the process plant is to generate a control action based on the comparison between the monitored controlled process variables and the control set points.
Fundamentally, MFM methodology distinguish the monitored process variables from the process objective, which means that the objective may not be directly associated with a function whose performance can be directly evaluated based on the monitored variable.
However, with the mostly adopted PI and PID type of controllers in the systems that MFM is invented to represent, the monitored process variables are contributing to the objective or main function state. In this paper, the control rules described applies only to this type of control functions.

Based on the MFM definition, the control function will act upon the failure of the fulfilment of the system objectives. This means the objective failures shown in Table 4 will influence the control function to actuate on its target functions, which then will compensate for the deviation that triggered the control actuation.
By using MFM models, this type of causality introduced by a control function can be traced though the control and process causal relations.
How a target function is actuated should be based on the internal control logic that is defined with the control function. The logic should match the control observation with the control actuation.
For the PI or PID type of controller the actuated function state can be mapped with main function state directly based on whether the actuation is done to the upstream or downstream to the main function.

In association with the objective failure criteria stated in Table 4, the following mapping rule in Table 5 can be defined for MFM control functions which is based on basic feedback control.
The first two column define the control function type and the actuation point, the second two column defines the known state or propositions regarding the control pattern. The last column explains the conclusion that can be made due to the MFM model and the existing state. Note that the control actuated function state is not described as abnormal state (high or low), but defined as a transient function state that describes the tendency for the function performance change.

3.3 Reasoning example

Given the simple example that shown in Fig.1, with the maintain control pattern, assuming the storage function sto1 has a high state (indicating the storage level is higher than the set point).

Table 5 MFM control influence rules (consequence)

control function conditions		known states		conclusions
control function type	actuation @	target/threat state	main function state	actuated function state
maintain	upstream	target false	high, high-high	decrease
			low, low-low	increase
	downstream		high, high-high	increase
			low, low-low	decrease
produce	upstream	target false	low, low-low	increase
	downstream		low, low-low	decrease
suppress, destroy	upstream	(high) threat true	high-high	decrease
	downstream		high-high	increase
	upstream	(low) threat true	low-low	increase
	downstream		low-low	decrease

According to the MFM causal rules defined in both Table 5, the following rule can be apply to generate a new proposition:

Condition

P1: sto1 is high

P2: tar1 is false (due to *P1*)

mco1 maintains tar1 by actuating at upstream

Conclusion

P3: tra1 decrease

The corresponding control action is to reduce the inflow rate.

A similar example can be given for the system and model in Fig.2. Assuming the storage function sto1 has a high-high state, the state of the threat thr1 will become true, where the following rule can be apply to generate a new proposition:

Condition

P1: sto1 is high-high

P2: thr1 is true (due to P1)

dco1 destroys thr1 by actuating at downstream

Conclusion

P3: tra6 increase

The corresponding control action is to open the control relief valve.

To test whether the rule is consistent with the intended control objective, the increased and decreased state for a MFM flow function should be able to propagate through the model by using the same causal reasoning rules that defined in previous literature [3].

In the Fig.1 example, the tra1 decrease will propagate downstream and generate the conclusion that sto1 should be decreased as a consequence, which compensate for the high state that triggered the control actuation in the beginning. The control influence path is:

sto1 high → tra1 decrease → sto1 decrease

In the Fig.2 example, tra6 increase influences tra3 to increase due to the mediate relation between the mass flow and the energy flow. Tra3 increase will given a proposition about sto1 to decrease, which compensate for the high-high state that triggered the control actuation. The control influence path is:

sto1 high-high → tra6 increase → tra3 increase → sto1 decrease

4 Case Study

By introducing the control influences into MFM, the MFM models can be used to analyze the controller behavior on top of the process deviation propagation. In [3], a MFM model for the PWR primary system is presented. The model is adapted to include the pressure and level control function in the PWR system to demonstrate the reasoning through MFM control functions.

The updated MFM model for the PWR primary system is shown in Fig.3.

In this MFM model, PRZ_efs represents the energy flow structure of the pressurizer in the primary system, and the RCS_efs represents the mass flow structure. As explained in [3], the model represents individual coolant loops as one coolant circulation which is represented by the function pattern of sto9-tra20-sto8-tra21-tra22-sto9.

Table 6 Control functions in the MFM PWR model.

Control function	Actuated function	Explanation
moc_heater	tra5	maintain the pressure by actuating on the heater
moc_sprv	tra19	maintain the pressure by actuating on the spray vlve
moc_porv	tra14	maintain the pressure by actuating on the power operated relief valve
moc_charging	tra26	maintain the coolant level by actuating on the charging pump
moc_makeup	tra24	maintain the volumn control tank level by actuating on the make up system

sto7 represents the pressurizer liquid level and sto5 represents the gas phase mass in the pressurizer. The detailed explanation of the MFM model can be found in [3] and therefore will be omit here. The model is updated by adding 5 control functions, three for pressure control and two for level control.

The control functions and their actuated function are explained in Table 6.

4.1 Reasoning scenario

A scenario is defined for testing the control rule. In the scenario, the pressurizer heater and spray valve are turned into manual control. The heaters are turned on for full capacity and where the spray valve are shut down to 0%. In this condition, a high pressure alarm will be triggered.

Based on this observed evidence, MFM reasoning is triggered to perform the consequence analysis, and the behavior of the control function can be examined. The storage function sto1 in the PRZ_efs represents the pressure level in the pressurizer. Thus the alarm can be translated as an MFM proposition to sto1 is high.

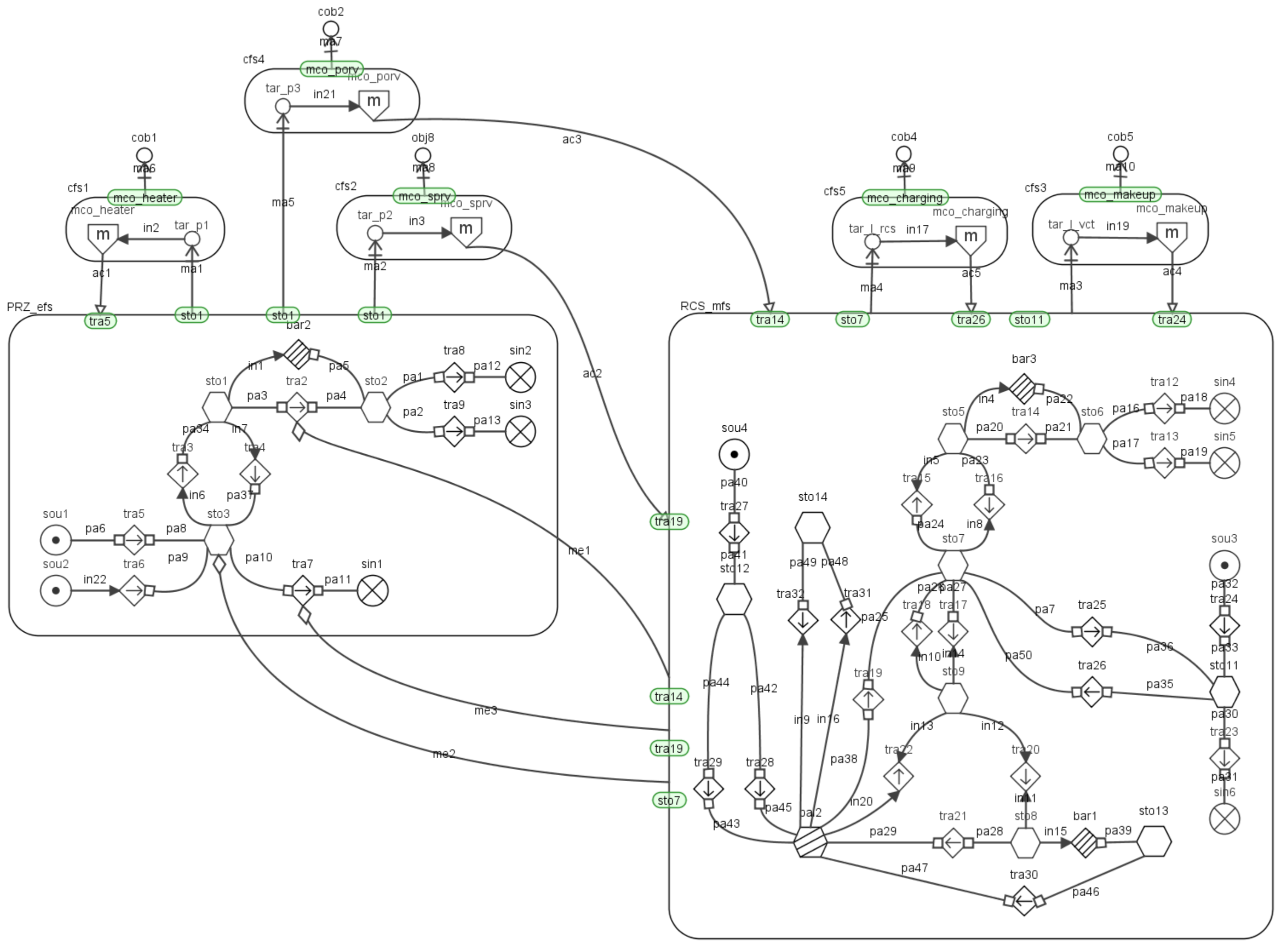


Fig. 3 MFM model for a PWR primary system with pressure and level control.

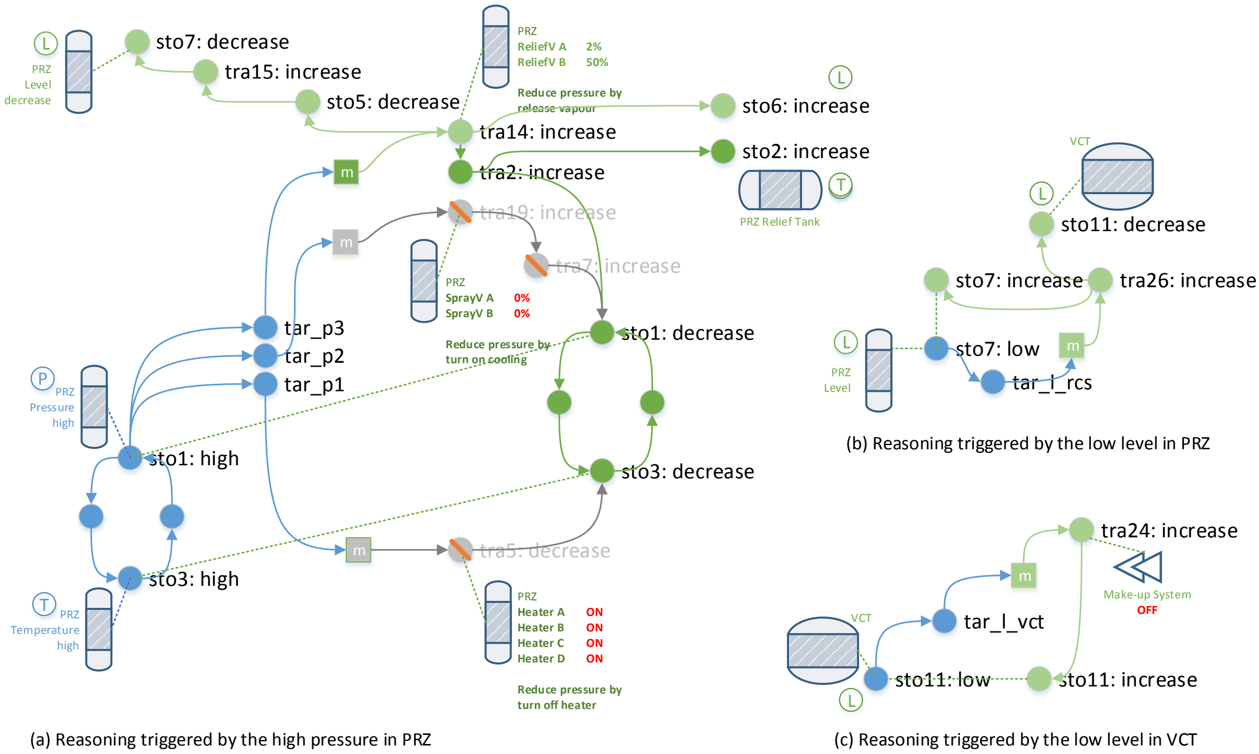


Fig.4 Interpreted reasoning result for the simulation scenario.
(process function state in blue, control influenced function states in green)

Based on this observed function state, MFM reasoning is triggered to perform the consequence analysis, and the behavior of the control functions can be examined.

Fig.4(a) shows the interpreted reasoning result generated from MFM reasoning software based on the high pressure (sto1 is high) state introduced in the model. The process function state are shown as blue dots in the diagram. Based on the process function, the pressure and temperature will influence each other which can be analyzed based on MFM causal reasoning for flow functions.
Adding the control function influences to the model, it further suggests that all the three control functions that control the pressure can be used to compensate for the high pressure situation, which should lead to a decrease of pressure and temperature. The control generated state are shown as green dots in the diagram.
However in this particular scenario, since both the spray valve and the heater are manually set to an opposite operation state, those actuation functions can not be used. The high pressure has to be controlled by the PORV.
The increase of the mass and energy that is released from the PORV will reduce the pressure in the system, but also reduce coolant in the RCS system. In the MFM model, this is presented as a decreased sto7 in the mass flow.

During the scenario simulation, no manual intervention is performed, thus the coolant level will be decrease continually which lead to a low level state for sto7. In the MFM model, sto7 is maintained by a control function that actuates the charging pump to increase the flow rate from tra26. This control actuation will compensate for the loss of coolant, but reduce the VCT level at the same time. The event propagation generated from the MFM model is shown in Fig.4(b).

Since VCT level is also maintain the by the control system, when the level reach a low state, the control actuation will inject more coolant to compensate for the reducing level in the VCT. This is demonstrated in Fig.4(c). The level of VCT tank did not drop below the control set point during the presented simulation, therefore the makeup system did not start. However if the situation progress with no human intervention, the makeup system is expected to start working.

5 Conclusion and future work

This work presented the first formulation and implementation of the MFM causal reasoning rules for control functions. It clarified the concepts and failure states for MFM target and threat, which are the basis for initiating control actuation. A case study of the PWR system is used to demonstrate how MFM reasoning including control functions can be a powerful tool to support the understanding of control actions in a complex system.

Several points should be address to further the study of using MFM to reason about control action.
Firstly, comparing the system configuration (e.g. valve position or pump setting) with the predicted control action can provide evidences for pruning the reasoning result regarding control function in MFM.
Secondly, an efficient interface that shows the process analysis together with the control reasoning analysis need to be developed to build a proper tool that can be used by the operators.
Thirdly, advanced controllers are being introduced to the industry in recent years. How to understand and represent more complicated control function should be investigated in the future.

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