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Control functions in MFM: basic principles

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Abstract: Multilevel Flow Modeling (MFM) has been proposed as a tool for representing goals and functions of complex industrial plants and suggested as a basis for reasoning about control situations. Lind presents an introduction to MFM but do not describe how control functions are used in the modeling. The purpose of the present paper is to serve as a companion paper to this introduction by explaining the basic principles used in MFM for representation of control functions. A theoretical foundation for modeling control functions is presented and modeling examples are given for illustration.

Keywords: functional modeling; complexity; supervisory control

1 Introduction

Modern industrial processes and technological infrastructures such as energy supply systems rely strongly on advanced control systems and human machine systems in order to ensure safe and efficient operation. The increasing demands to risk reduction and increasing efficiency have been met by a combination of automated control and supervision functions and by development of sophisticated decision support systems for the plant operator. These improvements have been gained by more extensive and efficient use of knowledge of the automated process in plant design and operation. Advances in information technology have also played a key role in this development.

These improvements obtained through increasing the level of automation has also resulted in more complex control systems designs and in more complex control logic which can be difficult to understand by a human operator. As a consequence, the risk of abnormal operational situations not anticipated by the control designer increases by the introduction of more advanced control logic. In such abnormal operational situations where the automation may fail to achieve its intended purpose the human operator should be able to evaluate the performance of the control systems so that he/she can diagnose the plant situation, and propose compensating actions. Such decision making require knowledge of the goals and functions of the control systems in the analysis of

the control situation and proposal of alternative control strategies. But knowledge of control goals and functions is clearly beyond the level of logic and algorithms and play also an important role in control design.

Existing approaches to control engineering do not consider purposes and functions of control systems as objects of explicit modeling. However, any control design contains implicit assumptions about the end and means of control. Control theory using differential equations and discrete event concepts for modeling dynamical systems do not offer concepts for modeling purposes and functions. Such qualitative information and conceptual structures which are significant aspects of control situations are treated informally as assumptions for the dynamic models.

Control systems designers may claim that they can read information about purposes from P&I and control logic diagrams. However, this information is not explicit in the diagrams but is inferred by the expert based on his knowledge about the design problem. It is therefore difficult to validate the information about control purposes and to communicate the information to other designers and plant operators. When ends and means of control are implicit it is also difficult to define, reason about and implement transitions between plant states which require different control strategies.

Multilevel Flow Modeling (MFM) is a tool for representing goals and functions of complex

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industrial plants^[1, 2] and has been suggested as a basis for reasoning about control situations^[3]. MFM has been introduced by Lind^[1] including the concepts for representation of control functions but without describing how the concepts are used. The purpose of the present paper is to serve as a companion paper to this introduction by presenting the theory and principles used in MFM for representation of control functions. It is assumed that the reader is acquainted with the introduction given by Lind^[1].

The paper will first introduce the control functions and their theoretical foundations in a theory of action types. We will then use examples to illustrate how the concepts are used when building MFM models including control functions. The examples have been chosen so that they can be used as templates which can be applied in other modeling situations. The examples have also been chosen so that the present paper can serve as a companion paper to Lind *et al.*^[5] where an MFM model of a nuclear power plant including several control systems is presented. It is here demonstrated that MFM can represent control systems for a complex system like a nuclear power plant but without giving explanations at the level of detail presented in the present paper.

2 Control functions in MFM

Previous MFM research has been focused on representing goals and functions of material and energy processes in industrial plants and technical infrastructures. Only a limited consideration has been given to the problems of modeling the control systems. Modeling of control system functions has proven to be more challenging than modeling functions of energy and mass processes^[3].

The question addressed in the following concerns the definition of the control functions shown in Fig. 1. The functions used for modeling material and energy processes (source, transport *etc.*) are closely related to understanding process plants as “flow” systems.

Control systems may as well be seen as information flow systems. But such a perspective do not convey control system purposes since the processing of information and the associated flows are only means used for implementing control functions. We need

therefore other functions to represent control in MFM. The control functions steer, regulate, trip and suppress shown in Fig. 1 were derived by Lind^[2] from a theory of action types developed by Von Wright^[4]. We will in the following show how the action types can be used to define the control functions in Fig. 1.

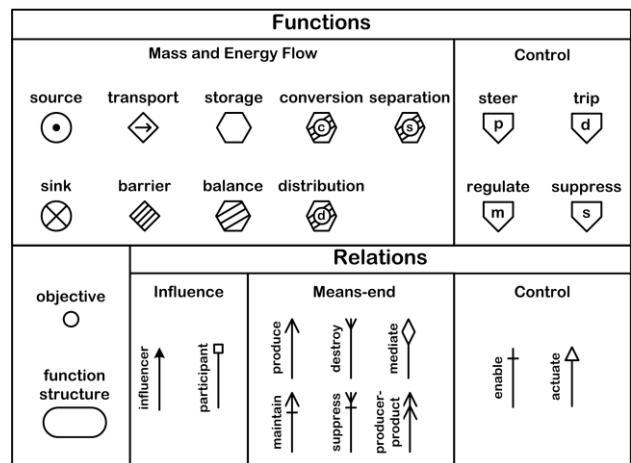


Fig. 1 MFM concepts and symbols (Lind^[1]).

2.1 Action theoretical foundations

We will first give a brief outline of the theory and use it to derive a logically complete set of elementary control actions. From these elementary control actions we will then derive the MFM modeling concepts for control functions in Fig. 1. The action theory provides also a foundation for defining the flow functions (storage, transport, barrier *etc.*). These applications of the theory are described in Lind^[2] but will not be discussed here.

2.1.1 Elementary action types

The action theoretical foundation for the control functions in MFM was derived by Lind^[2] from the work of Von Wright^[4] by a semantic analysis of his action types. Von Wright's theory provides a logical definition of the concept of action based on the concept of change.

A change is a temporal succession of two states and can be formally be represented by the schema pTq where p is a proposition which is true before the change, T is a temporal operator (then) and q is a proposition which is true after the change. However, as pointed out by Von Wright, an action is not only a change in state of affairs, it has also a counterfactual

aspect because the change would not occur unless the action was done. A logical definition of an action must therefore also refer to the hypothetical (not actualized) state of the world that would obtain if the action was not done. In this way an action can be defined by the schema $pTqIr$ where I (instead) is an operator relating the actualized state q with the hypothetical state represented by the proposition r .

It should be noted that the logical definition of an action provided by the schema $pTqIr$ is only capturing causal aspects of the action. Other aspects normally attributed to actions such as agency (who is acting), its purpose or intention and the object of action are not included in the schema.

Table 1 Von Wright's elementary action types

Description	Schema
<i>produce p</i>	$\sim pT pI \sim p$
<i>maintain p</i>	$pT pI \sim p$
<i>destroy p</i>	$pT \sim pI p$
<i>suppress p</i>	$\sim pT \sim pI p$

Von Wright defined a very limited set of elementary action types by only allowing the states to be described by a proposition p and its negation $\sim p$. With this restriction there are only eight possible types of so-called elementary actions. The eight types can be subdivided into two groups of four interventions and four omissions^[2]. The four elementary intervention types shown in Table 1 are important for categorizing control actions. The omissions are also relevant but will not be discussed here.

Each elementary action type in Table 1 is defined by its schema and a description. The schema $\sim pT pI \sim p$ has accordingly the description *produce p*. The significance of the descriptions for representing intentions of actions is explained in the next section.

2.1.2 Descriptions of elementary actions

At the outset it may seem unnecessary to use all four elementary action types since they can be reduced to two by simple logical substitutions. The possibility of

a reduction can be demonstrated by considering the schema of one of the action types e.g. $\sim pT pI \sim p$. By substituting p with $\sim p$ in this schema we get $pT \sim pI p$. Note however, that the corresponding descriptions *produce $\sim p$* and *destroy p* are distinct. So, even though the reduction is logically possible it is accordingly not desirable from a semantic point of view. The two descriptions *produce $\sim p$* and *destroy p* refer to the same physical action (defined by the schema) and may therefore be considered the same but they have different meanings according to the descriptions. The description *produce $\sim p$* refer to the action of an agent intending to promote a new state $\sim p$ whereas *destroy p* refer to the action of an agent who is opposed to the situation defined by p (and therefore destroy it). As demonstrated by Lind^[2], descriptions of an action can be used to distinguish between intentions of agents performing the same physical action (defined by the schema) but having different intentions (defined by the descriptions).

The distinction between promotive and oppositive actions introduced here is highly relevant for the representation of safety related control actions. Since the purpose of safety related control actions is to prevent or suppress undesirable plant states they clearly belong to the category of oppositive actions.

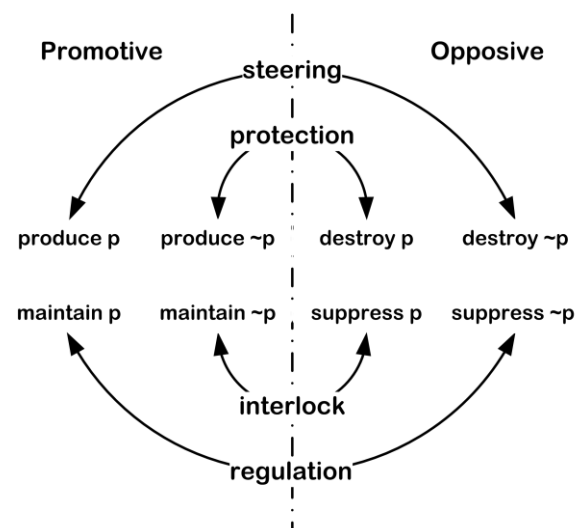


Fig. 2 Interpretations of control actions.

2.1.3 Elementary control actions





The elementary action types shown in Table 1 have one to one relations with established control engineering concepts (steering, regulation, interlock and protection). The distinction between action schema and description introduced above can also be

applied to control actions. These correspondences are shown in Fig. 2.

2.2 Control functions

Von Wright's action types and the extensions with descriptions proposed by Lind [2] provide a formal foundation for the definition of elementary control functions. The transition from the action types to MFM concepts and symbols is actually quite straight forward as shown in Table 2.

Table 2 Control functions in MFM

Task	Symbol	Purpose
Steering		Ensure that p is produced
Regulation		Ensure that p is maintained
Tripping		Ensure that ~p is produced
Interlocking		Ensure that ~p is maintained

The control function symbols in Table 2 are derived directly from the two components of the action descriptions. The verb is represented symbolically by an "inverted house" with a label indicating the type. The proposition defining the intended result of the action, its target, is represented by a circle as other goals or objectives in MFM.

Control functions are combined with the standard MFM concepts into so-called control patterns exemplified in Fig. 3. The control function con1 is related to a flow structure mfs1 by an actuation relation ac1. The label associated with the actuation relation contains the name of the flow function (XX) which is influenced by the control function. The target node (objective) obj1 is connected with the flow structure mfs1 by a means-end relation ma1 (here a maintain relation). The target node defines a constraint on the state of flow functions (YY) in mfs1. The basic control patterns in Fig. 3 includes also a control performance objective cob1 which is connected with the control structure cst1 through a means-end relation (here a maintain relation). The structure shown in Fig. 3 is an example taken from a whole ensemble of possible control patterns [2].

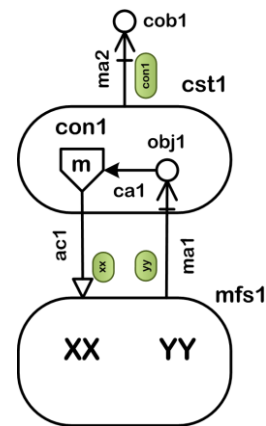


Fig. 3 Basic control pattern in MFM.

2.2.1 Control cascades

Control patterns can be combined as shown in Fig. 4 to represent the functions of a control cascade. The cascade includes here two control functions con1 and con2 where con2 determine the objective of con1 via the actuation relation ac2. We will illustrate the use of the basic control pattern and the cascade pattern by examples in the following.

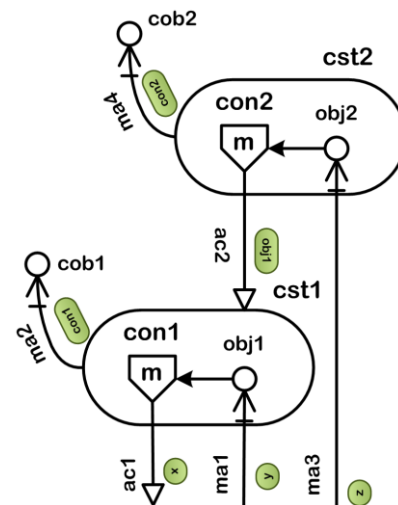


Fig. 4 A cascade pattern.

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 Modeling examples

The MFM concepts for representation of control functions will now be illustrated by some examples. The first example is a regulated water tank and the

second example is a heat transfer loop.

3.1 A regulated water tank

The regulated water tank example shown in Fig. 5 is used to illustrate the principles used to represent a simple feedback control loop. The purpose of the control system is to regulate the water delivered by the pump f_i so that the water level is maintained at a desired set-point h_{ref} when the outflow f_o is changed. Figure 6 shows the MFM model of the regulated water tank. Below we will explain the model in detail.

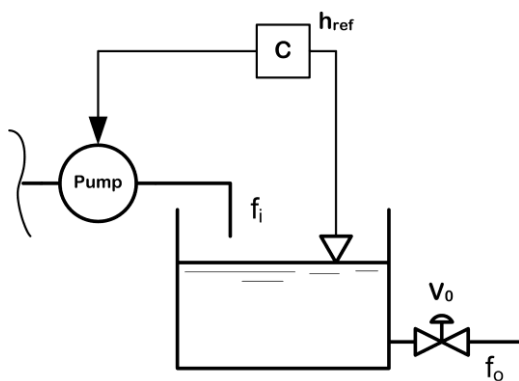


Fig. 5 A regulated water tank.

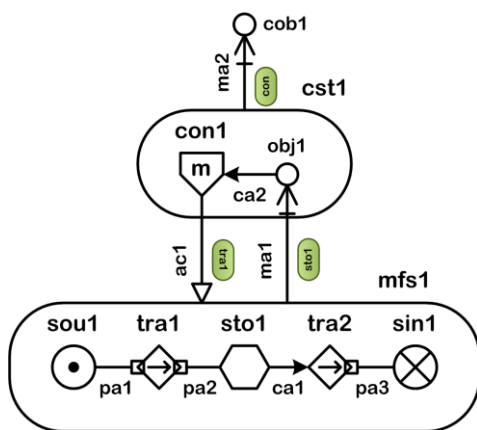


Fig. 6 MFM of regulated water tank (Fig. 5).

3.1.1 The MFM model

The functions of the tank process are represented by the flow functions in the flow structure $mfs1$. The source $sou1$ represents the environment delivering water to the pump. The transport function $tra1$ represents the water transfer from the environment to the tank provided by pump. The source and the transport are related by a participant relation $pa1$ because the environment is assumed not to influence the flow of water which is determined by the pump.

The transport function is also connected by a participant relation $pa2$ with the function $sto1$ representing the storage of water provided by the tank since the state of the storage (amount of water) cannot influence the flow of water delivered by the pump. The function $tra2$ represents the transfer of water out of the tank provided by the outlet pipe including the control valve. It is connected with an influencer relation to $sto1$ since the level of water influences the transfer of water out of the tank.

The function of the controller maintaining the water level in the tank is represented by the control structure $cst1$. The regulation function of the controller is represented by $con1$ and the set-point value (h_{ref}) 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 ($tra1$) in $mfs1$ which is actuated by the control function. Note that the pump therefore in this model has two functions, to transport the inlet water ($tra1$) and to actuate ($ac1$) the tank process.

Finally, the control structure $cst1$ is connected with the control 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.

3.2 A heat transfer loop

The heat transfer loop described in the following is a little more complex than the tank example by including several levels of means-end abstraction and a cascade control system. The example is taken from Lind, *et al.* [5] where the MFM model is used as a template in the development of an MFM for the Monju NPP. Below we will give a more detailed explanation of the control functions including a temperature controller which is included but not discussed explicitly in Lind, *et al.* [5].

The heat transfer loop shown in Fig. 7 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 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.

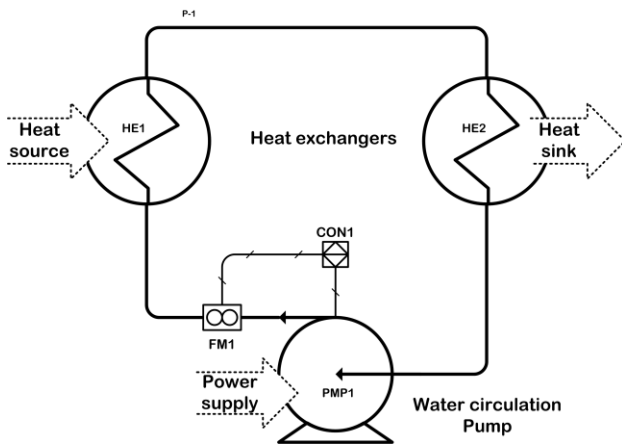


Fig. 7 A heat transfer loop example.

3.2.1 MFM of heat transfer loop without control

Figure 8 shows the MFM of the heat transfer loop without control which contains three functional levels comprising an energy flow structure efs1, a mass flow structure mfs1 and an energy flow structure efs2.

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 circuit and tra2 and tra3 represents conversion of the energy into kinetic energy of the water (tra2 and sin1) and friction losses in the circulation loop (tra3 and sin2).

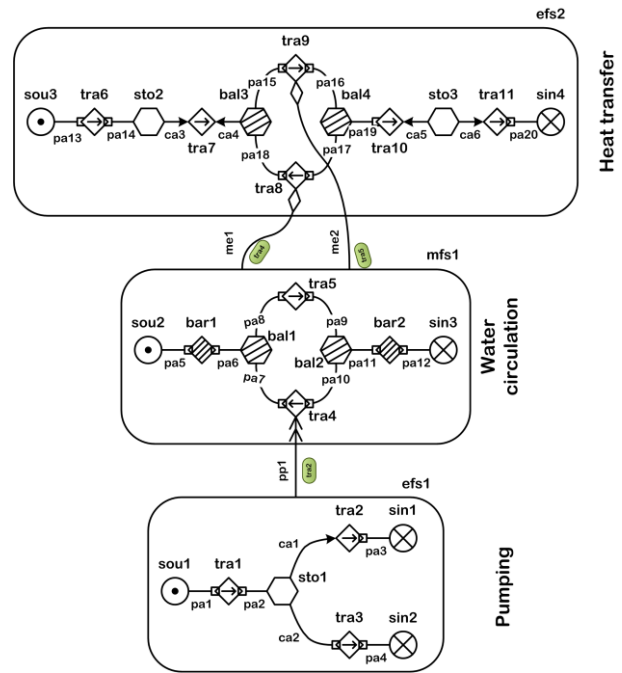


Fig. 8 MFM of the heat transfer loop without control.

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 producer-product relation pp1 [2]). Since the water is re-circulated the two ends of the transport function tra4 are connected with the function sto2 representing the water storage 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.

Flow structure efs2 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 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.

3.2.2 MFM of heat transfer loop with flow control

When the principles for representing control functions described above are applied to the heat transfer loop we obtain the model shown in Fig. 9. 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). The actuation relation act1 connects the control function con1 with the transport function tra1 as indicated by its label.

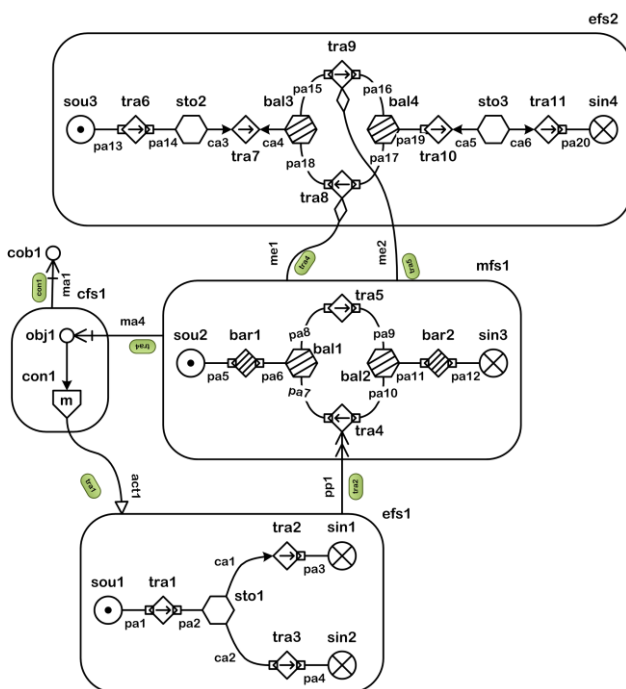


Fig. 9 MFM of the heat transfer loop with flow control.

Note that the MFM shown in Fig. 9 is an example where a control function includes several functional levels (efs1 and mfs1). The control function in the regulated water tank included only one functional level (mfs1 in Fig. 6). This means that the means-end

relations can be included in the control function (pp1 in Fig. 9).

3.2.3 Extension with temperature control

We will now extend the heat transfer loop as shown in Fig. 10 with a temperature controller which is connected to the flow controller in a cascade configuration. With this extension we can illustrate how the cascade pattern shown in Fig. 4 is used in a concrete example.

The purpose of the temperature controller CON2 is to regulate the temperature in heat exchanger HE1. This is done by compensating deviations in the temperature measured by the instrument TM1 by increasing or decreasing the set point for the flow of circulated water when the temperature increases or decreases.

The MFM model with the additional control function for temperature is shown in Fig. 11. We have here adapted the principles from the regulated tank example to model the temperature control functions. The temperature is related to energy storage in HE1 (sto2) and is regulated by controlling the energy transferred to HE2. This energy transfer is represented by the transport functions tra8 and tra9 in the MFM model. In the heat transfer example in Fig. 11 the storage contents is regulated by the outflow (tra9) of sto2. In the regulated water tank example shown in Fig. 6 the storage (sto1) contents was regulated by the inflow (tra1). It is realized that both control strategies can be represented and distinguished in the respective MFM models.

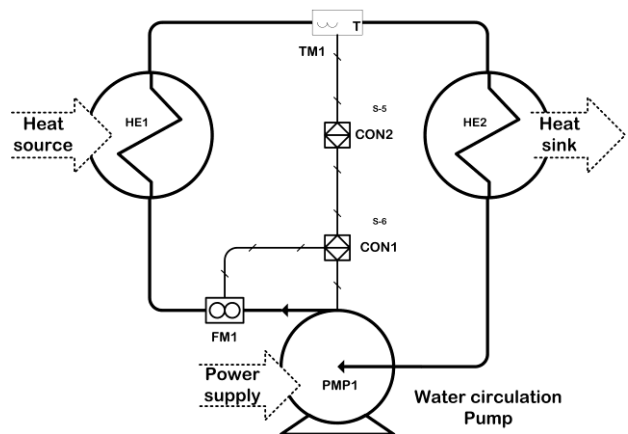


Fig. 10 The example extended with a temperature controller.

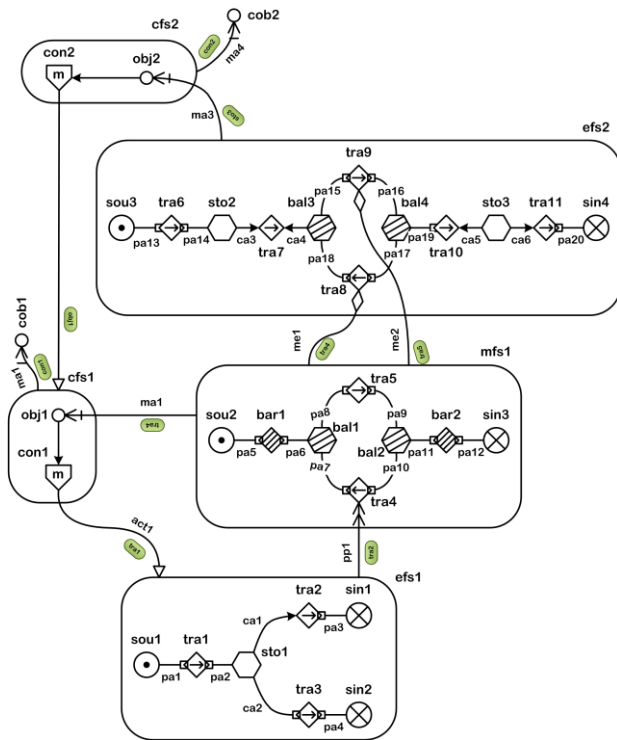


Fig. 11 MFM model of heat exchange loop including functions of both the flow and the temperature controllers.

Note that the control cascade pattern is used in Fig. 11. Function con2 representing the function of the temperature regulator is connected by an actuation relation to cfs1 which represents the functions of the flow regulator. It is realized that in this case the control cascade includes three functional levels through the means-end relations pp1, ma1, ma2 and ma3.

4 Discussion

The paper demonstrates that MFM can be used to model goals and functions of automated processes. The examples presented show the entanglement of control and process functions and illustrate that the modeling of control functions and process functions cannot be meaningfully separated in means-end analysis of automated plants.

Lind [2] suggest that rules for reasoning about control in MFM models can be developed. Ongoing work by Heussen *et al* [6] develop such rules for reasoning about controllability in power systems applications.

5 Conclusions

The paper has presented basic principles for the representation of control functions in MFM models. The paper presents an action theoretical foundation for control functions in MFM and demonstrates the application of the concepts by means of two examples.

The paper is a companion paper to the MFM introduction presented by Lind [1] and to the paper by Lind *et al* [5] presenting an MFM model of a nuclear power plant including several interacting control loops.

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