Plant Modeling for Human Supervisory Control[1]

Morten Lind
Department of Automation
Technical University of Denmark
DK 2800 Lyngby Denmark
email: ml@iau.dtu.dk

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ABSTRACT

The paper provides an overview of Multilevel Flow Modeling (MFM) and its application for design of displays for supervisory control of industrial plant. The problem of designing the information content of supervisory displays is discussed and plant representations like MFM using levels of means-end and part-whole abstractions are proposed as a solution to this design problem. The basic concepts of MFM are explained and its use in reasoning about means and ends and part and wholes in diagnosis are illustrated in detail by an example. A deeper elaboration of the semantics of MFM is also provided by an analysis of the relations between levels of abstraction. It is also described how MFM support reasoning about control actions by defining levels of intervention and by modal distinctions between function enablement and initiation.

1 INTRODUCTION

One of the aims of current research in industrial automation is to improve the reliability and availability of plant operations by the development of new principles for the human-machine interface. The research effort is a response to a series of serious plant incidents in the past which clearly demonstrated that bad design of the HMI can be the cause of operational errors.

Problems caused by bad HMI design may be divided into errors related to the contents of the information mediated by the interface and human error related to the form or expression given to the information through visualisation, text and sound. The latter types of error caused by inadequate expression or organisation of the information in the interface are important and their acuteness is increasing with the introduction of multimedia technologies. However we will here only discuss problems related to bad design of the information content.

1.1 The Problem of Information Content

Problems with information content arise if the plant status information displayed to the operator is not sufficient or not adequate for his current task. The operator may therefore get a wrong conception of the plant situation and his task and will be prone to make erroneous decisions. Often the displayed information are simply the values of all plant parameters that is aquired by the plant instrumentation. The information extracted from the measurements may also be inadequate. For example, the interface may display the measured value of a plant parameter even though the time derivative of the same parameter convey the information necessary for evaluation of plant state. Or, the interface displays the individual values of a set of parameters, whereas their combination in value patterns contains the information required for a supervisory task. Such interface systems make it difficult for the operator to interpret the situation and to evaluate his goals. The interface introduces a socalled 'gulf of evaluation' (Norman, 86) and increases the probability of human error. Similarly, operators may have problems with interfaces where it is not immediately obvious how to intervene i.e. with systems having a 'gulf of execution.' The operators intention may be to start a cooling system but the interface does not have a button for that purpose and he has to realise his intention by decomposing it into a complex sequence of operations on components and subsystems of the cooling system. Errors can then occur if it is not obvious for the operator where, when, how and by what means to intervene in the display system. A similar situation may arise when a plant disturbance can be handled by several alternative courses of action that each have different undesirable side effects.

These problems of information content are of particular importance when coping with infrequent disturbances in high risk plants with complex interactions between subsystems. Frequent disturbances usually do (or should) not have serious consequences and operator misconceptions may therefore be tolerated. In addition, operators learn to cope with frequent disturbances. Furthermore, wrong decisions may not have serious consequences if interactions between the plant subsystem are weak.

Complex plant interactions create problems for the design of human machine interfaces because it is not a trivial task to define the plant information that is required in order to understand what is going on in the system especially in disturbance situations. The mechanical and thermal processes in the plant may include complex patterns of interactions created by e.g. recirculation of energy or materials. The automated control systems create also complex dynamic interactions between plant components and subsystems that are difficult to understand by the operator if not represented properly in the interface. However, the interaction between automated controls and their responses to operator intervention can only be understood fully if it is seen as a goal oriented activity. Incidents in industrial plants have actually been caused by the operator ’fighting’ the automated control system. In such situations the operator either did not understand the goals or mode of working of the automation or had a misperception of his own task. The development in intelligent automation leading to more complex structure and behaviour of the automated systems makes this HMI problem even more acute. Advances in this area may also be used to create supervision and control systems that allow dynamic allocation of control tasks between the operator and the machine. In order to avoid human error in such systems it is neccessary that the operator understand the purposes, objectives and workings of the automated systems and that this understanding is supported by the information presented in the interface.

1.2 Plant Modeling for Display Design

A systematic approach to the solution of these problems in the design of human machine interfaces requires modelling concepts and a methodology to define the information to be mediated by the interface, including information about plant conditions and about plant interventions to be supported by the interface. Such methodology should allow a specification of the information in the interface independent of the available means of instrumenting the plant i.e. the sensors and the actuators. However, given the specification and knowledge about the plant instrumentation it is also necessary to develop methodologies for mapping the data acquired from the measurements into the required contents of the interface. This mapping problem can be difficult to solve especially in cases where the plant is not equipped with the proper type or amount of instrumentation. Another mapping problem is the translation of intentions into the actuation of plant equipment. Again, problems can arise if the plant is not properly instrumented so that a given intention only can be accomplished indirectly as a consequence or side effect of an action that can be implemented in the plant (start the cooling by starting the pump). These mapping problems will not be discussed further in the present paper. The remainder of the paper is concentrating on concepts and methodologies for modelling information content.

1.3 Research in Plant Modeling for Human Supervisory Control

Ongoing developments of socalled cognitive engineering approaches to HMI design apply plant representations based on levels of means-end and part-whole abstraction. This research include the work on abstraction hierarchies and ecological principles for HMI design by the RISØ group (Rasmussen, 1986) (Rasmussen et. al., 1994) and Vicente and his coworkers (Bisantz et. al., 1994) and the research of the author and his group at DTU. The aim of DTU group is to develop integrated approaches to conceptual design of automation systems, knowledge based systems for diagnosis and planning and MHI interfaces for supervisory control of industrial plant. Multilevel Flow Modelling (MFM), described below is a result of this activity. MFM was originally developed by the author as an attempt to formalise the abstraction hierarchy proposed by Rasmussen, but it is now seen as an independent development based on the same basic ideas of levels of means-end and part-whole abstraction as the abstraction hierarchy (Lind, 1999a). An overview of MFM was presented in Lind(1994) and the aim of the present paper is to give a more in depth discussion of the basic principles of MFM and to report on recent developments in its semantics (Petersen et. al. 1998). Thus, even though the basic concepts have been fixed for a while, MFM is still under development. Ongoing research (Lind, 1999b) is seeking to consolidate the semantics of MFM even further through an analysis of action concepts derived from VonWright's theory of action (VonWright, 1968). The basic ideas behind this development were already introduced in (Lind, 1994) by the derivation of four basic categories of control functions. The present paper does not include results from this new work and should therefore be considered as a report on the current status of 'ortodox' MFM. This means also that the paper does not include the extensions of MFM with dynamics proposed by VanPassen and Wieringa (1999).

2 MULTILEVEL FLOW MODELING

The purpose of MFM is to represent goal structures and their relationship to underlying causal mechanisms of the plant in a formalised way. The basic idea of MFM can be introduced by a concrete and simple engineering example: the water circulation system of a central heating system. Such systems can be described at the following three levels

- Component level

- Function level
- Intentional level

At the component level we identify physical objects which are connected into a system. The heating system consists for instance of a boiler, a radiator, a pump, an expansion tank, valves and pipelines. Components in a technical system are not only physical objects, they also carry out definite functions alone or in interaction with other objects, they are used to achieve objectives satisfying needs i.e. they are designed and operated for a purpose. The result of these interactions are described on the functional level.

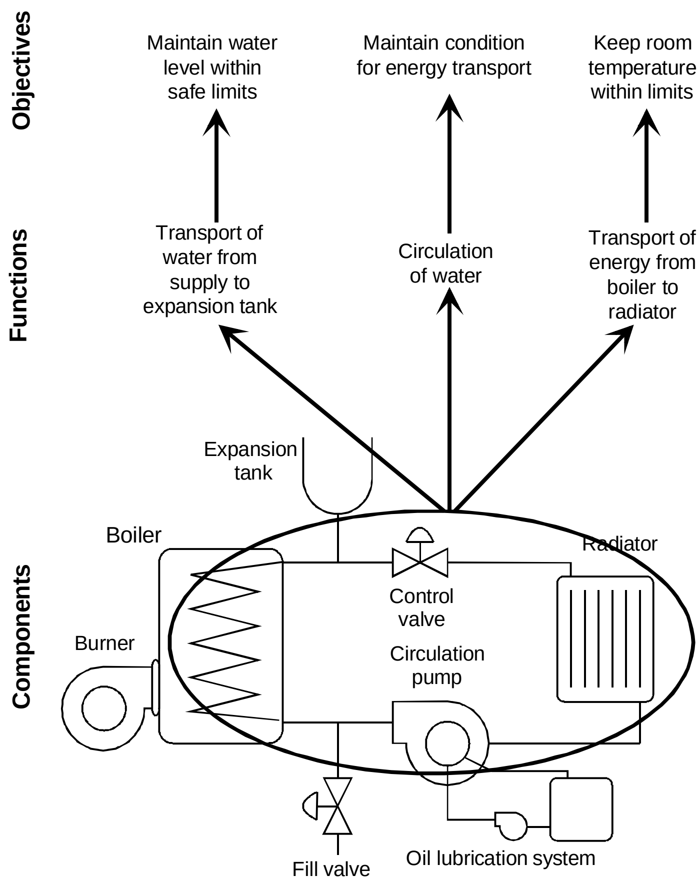

Fig. 1. Objectives, Functions and Components of the Water Circulation in a Central Heating System

The water circulation circuit in a central heating thus serves three functions namely 1) to transport water from the supply to the expansion tank, 2) to circulate the water and 3) to transport energy from the boiler to the radiator. For many purposes knowledge of the underlying component realisation is irrelevant and only knowledge of system functions is required. Functions are realised by mechanisms that are causally related and serve definite objectives. The function of the piping in the heating system is to circulate water. The objective of the circulation is to bring the heat to the radiator which radiates in order to achieve the objective of maintaining a certain temperature in the room. Objectives are not causally related but are part of a logically ordered system of values, goals, objectives and preferences. Consequently, we may expect to be able to analyse structures of goals and objectives by logically related conditionals.

It is now clear that when we are diagnosing a technical system we may find faults on all three levels. The diagnosis may lead to a failed component that should be replaced or a failed function that should be restored by using alternative means of realisation.

Let us now introduce the MFM concepts that are used to create a conceptual model that formalise and represent all this plant knowledge.

2.1 MFM Relations

There are several relations between the levels of objectives, functions and components. Each of the relations will be discussed separately. Table 1 shows the symbology used for each of the relations. The example presented later will show how the relations are used .

<u>2.1.1 The Achieve Relation.</u> First there is the relationship between objectives and functions. Objectives are achieved by performing certain functions. Therefore we have an achieve relation (A). The (A) relation is a means-end relation where the objective is the end and the

function or systems of functions are the means. When using the (A) relation, the function represent the purpose of the material and energy transformation processes. A special type of achieve relation is used to represent a control system as a means for achieving an objective. This specialized relation is called an achieve-by-control relation (A-C).

2.1.2 The Condition Relation. An objective can also define a condition that is neccessary for the enablement of a function. This conditioning is expressed by a relation (C) between the objective and the function.

2.1.3 The Goal-Objective Relation. In addition to the A and A-C relations that link objectives and functions, we also need to express relations between goals and objectives. Goals and objectives can be related in several ways. One important relation can be derived by making a distinction between a system S1 having a need (i.e. a pump needs/lacks lubrication) and the system S2 that has been assigned the role of satisfying the need (the oil pump and associated components of the lubrication system). The decision to satisfy a need X (lubrication) of S1 is expressed in a design goal (provide lubrication) which again is reflected in an objective Y (maintain oil flow) to be achieved by means of the resources of S2. The main point here is that the goal 'provide X' is defined relative to the needs X of S1 and the objective Y is relative to S2. The objective Y can be considered a technification of the goal. This relation, called a goal-objective relation (GO), describe that the achievement of the objective is a sufficient condition for the satisfaction of the goal. Note that a goal can often be met through the achievement of several alternative objectives.

2.1.4 The Goal-Subgoal Relation. A goal can also be subordinate to another goal. This relation is called a goal-subgoal relation (GSG) and is used to represent goal trees. A goal tree describes the interdependence between needs in a complex system. Note that the GSG relation should not be confused with the GO relation introduced above.

2.1.5 The Producer-Product Relation. Functions can be related through a causal relation called a producer-product (PP) relation. This relation is used when the temporal interactions between a set of functions (a process) result in a product that again serves another function in the system.

2.1.6 The Mediation Relation. Functions can also be related through another causal relation called a mediate (M) relation. This relation is used when a system has the role of being an intermediate between an agent and another system that serve as an object of action. An example of such a mediation could be the transportation of energy by the pumping of water. Here, there is a mediate relation between the pumping function and the transportation of energy. The mediation has no temporal connotations.

2.1.7 The Connection Relation. Functions can also be related through socalled connections (FC). A functional connection provides a contextual linkage of two functions meaning that they relate to the same goal perspective or that they share objects (they change properties that belong to the same object or substance. Further aspects of these relations are discussed in (Petersen and Lind, 1998).

2.1.8 The Realization Relation. Finally, functions can also be related to the physical components that are the means for their realization. Note that a function can sometimes be realized by several alternative means of realization.

By using these relations we are able to express complex networks of relations between goals and functions which are means for realising these goals and goals which are conditions for the proper operation of functional systems. The relations and the symbol used in MFM models are summarized in Table 1.

………………………

Insert Table1 here

………………………

2.2 Flow Functions

Multilevel Flow Modelling also define a set of elementary functions that are used in the modelling together with the relations described above. These socalled flowfunctions and the symbology used in the modelling are shown in Table 2.

………………………

Insert Table 2 here

……………………….

Each of the functions represent an action on a substance which may be mass, energy or momentum. The different substances are indicated by the symbology. In action terms a source provides a substance i.e. makes it available. Similarly a sink removes substances. A transport changes the spatial location of a substance and a barrier prevents flow.

The flow functions used in MFM at the present stage of development comprise an important but not yet complete set of functions required for modelling energy and material processing systems. Research in structural semantics (Greimas, 66) suggest that the set of functions is an interesting one by being in correspondence with socalled actants (Poulsen, 1997). However, it is not yet clear whether this insight from linguistics is valuable in the context of modelling engineering systems. It is not obvious that the adequacy and completeness of the elementary functions can be decided on a linguistic basis only. It is also an empirical question i.e. does the set cover the needs and are they convenient to use for a domain expert?

2.3 Views

Due to the many relations involved, an MFM model in its entirety is a complex information structure that lends itself to implementation in a knowledge base. It is often convenient to segment the model into submodels representing a particular section or view of the model, in particular when the model is presented on a two dimensional medium like paper or a computer screen. Views can also be convenient when building MFM knowledge bases as a means to separate different types of plant knowledge according to their relevance for a particular type of task. Two types of views are defined for this purpose. The first view type is a goal-objective view presenting goals and objectives an their relations (GSG and GO). The second view type is an objective-function-component view presenting relations between objectives, functions and components. Examples illustrating the use of views are presented below.

2.4 A Modeling Example

In order to explain the use of MFM concepts we will discuss a model of the central heating system depicted in Fig. 1. The example illustrates the general features of MFM models.

2.4.1 Goals and objectives of the central heating system

The goals and the associated objectives for the example are shown in the goal-objective view of the MFM model, Fig 2. The description of objectives refers to system function f7, f8, f23 and f26 shown below in Fig. 3. The view also shows that the goals can be organised into a hierarchy through the GSG relations (note that a dummy aggregate goal is introduced). Actually, this hierarchy is a reflection of an underlying objective hierarchy that can be derived as a special subview of the objective-function-component view (not discussed in this paper). It is seen that each goal represents a need or requirement of a subsystem – a state or condition that should be provided by another system. The corresponding objective represents a translation of this requirement into a condition to be provided by means of another system. Take G3 as an example. This goal describes the need for a rotable pump impeller (if the impeller cannot rotate the pump is not able to transfer momentum to the water). This need is met by the system designer through the installation of a lubrication system. The lubrication system is operated according to the norm defined by objective O3.

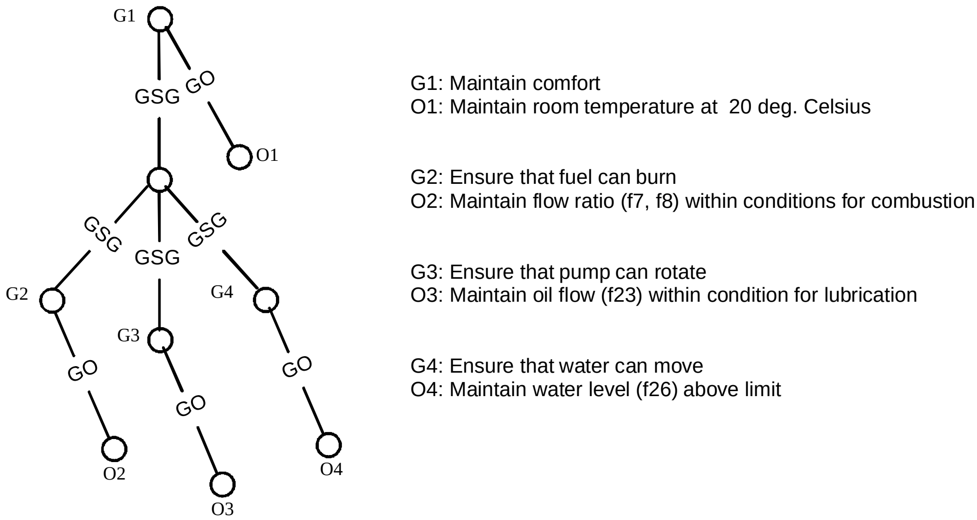

Fig. 2. Goal-objective view of the MFM for the Central Heating System

It is seen that the relation between a goal and its corresponding objective represents a design decision. In cases where the designer has provided alternative means of satisfying a goal, an operational choice should be made by the system user (controller). The preferences used to make the decision could then be included in the model as relations between the objectives. These relations will not be discussed here.

2.4.2 The Objective-function-component view

The view depicted in Fig. 3 describes how objectives are met through system functions and how these functions are implemented by systems components. This view actually is composed of six subviews each representing an objective, its underlying functions and the components realising the functions. The subviews in the model can be indicated by the triples

[O1, Production of Energy, C1],

[O2, Combustion of Fuel, C5]

[f4, Circulation of Water, C2]

[f14, Production of Momentum, C3]

[O3, Circulation of Oil , C6]

[O4, Maintaining Water inventory, C4]

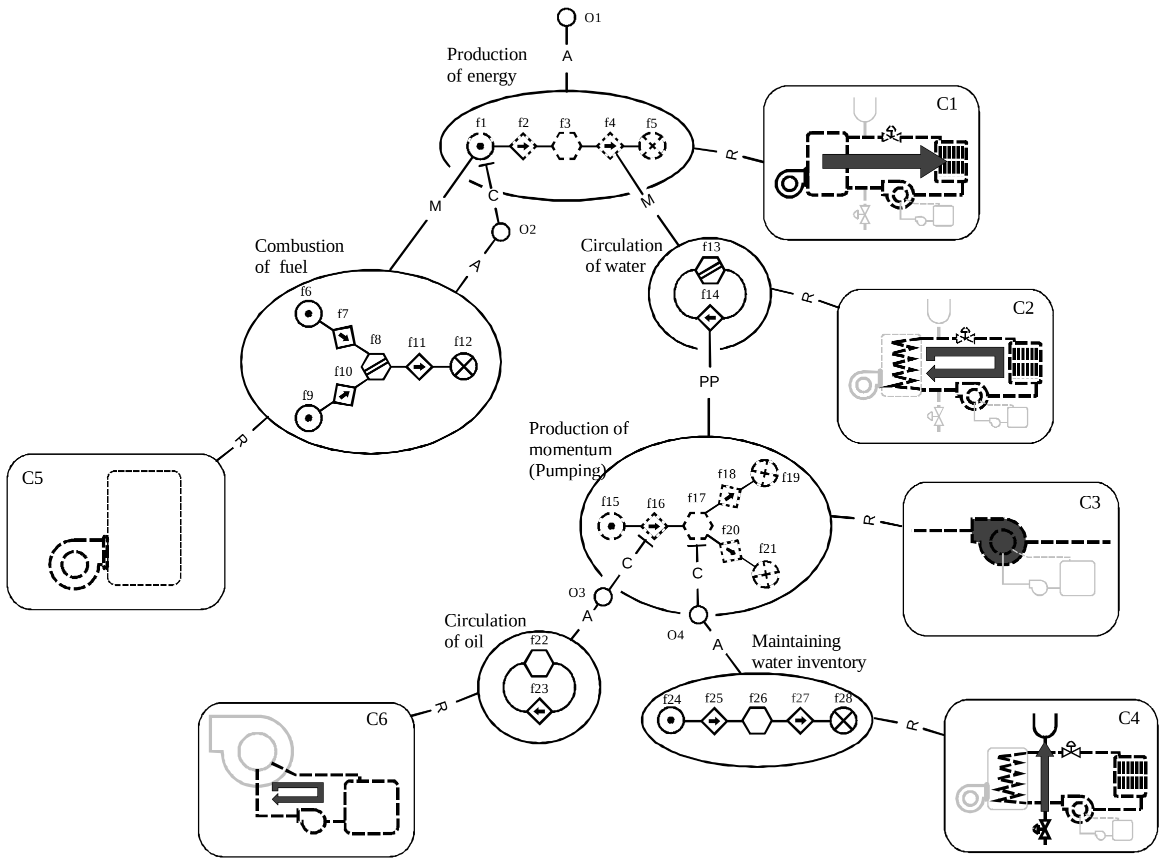

Fig. 3. Objective-Function-Component view of the MFM for the Central Heating System

It is also seen that these subviews are interconnected through the condition and mediate relations. As an example take the lubrication system C6 which is providing oil circulation in order to satisfy O3, which is the lubrication condition for the pump impeller, so that the impeller can transfer energy (f16) from the motor to the water. The energy transfer is again a means for pushing the water, expressed as an energy transport (f18) in the model. The transfer of energy (f14) from the impeller to the water in turn produces the movement of water, and by being circulated, the water transport heat energy (f4) from the boiler to the radiator. Finally, the transport of heat is a means for achieving the overall objective O1 – to maintain room temperature. The model describes in this way how each of the subsystems are connected in a network of means and ends. Note also that the model shows how the same physical components may serve several functions at the same time. The components that make up the water circulation loop are good examples to illustrate this. If we start at the bottom of the model (C4) we can see that these components provide functions for the management of water inventory. At the same time, the same components provide the water circulation function (C2) and the transfer of energy from the boiler to the radiator (C1).

This capability of representing multiple and interconnected perspectives of the same system is one of the most distinctive features of MFM. Perspectives are anchored in the objectives and the ascription of functions to system components and subsystems are relative to the objectives. It is not meaningful to ascribe a function to an object without indicating the context of objectives or goals describing what the object is used for.

2.4 Part-whole Relations

The MFM model comprises three types of part-whole relations. The first type is the GSG relation that relate a goal with its subgoals (Fig 2). The second type of relation is the relation between a functional aggregate and its parts- the flow functions. This is exemplified in Fig 3 by the aggregates describing production of energy, combustion of fuel, production of momentum, circulation of oil and the maintainance of water inventory. Each aggregate is decomposed in a set of flow functions. The third type of part-whole relation is the relation between an agggregate of plant components (C1, C2, C3, C4, C5 and C6) and the plant components (pump, tank, boiler, burner etc.).

Note that an MFM model provides an explicit coupling of different levels of means-end and levels of part-whole abstraction. However, it should be emphasized that the two decompositions are not simply connected as suggested by e.g. Rasmussen(1986) in his socalled Abstraction Hierarchy. This can be illustrated by the MFM model in Fig 3. According to Rasmussen there should be a close correspondence between the levels of decomposition of goals and functions in the means-end dimension and the levels of decomposition of the plant into subsystems and components. This is clearly not the case in the example. The physical aggregates C1, C2, C3 and C4 realize goals and functions that are organized in a means end hierarchy but do not themselves form levels in a hierarchy of physical decomposition (C4 is not subordinate to C3 even though their functions are).

2.5 Means-end and part-whole reasoning in MFM.

The rich information structure of MFM can be used to reason about means and ends in failure diagnosis and planning of control actions. The types of explanations supported by MFM are shown in fig. 4 below in a subsection of the MFM model of the central heating system. The model can be used to answer *why, what, how* questions as shown. All these questions have the same focus namely f14 and the answers that can be derived from the model are based on the means-end relations in the system. Thus when asking the question 'why is the water transported' (f14) we can find the answer on the level above in terms of f4 representing the transportation of energy. In other words, the reason for circulating the water is that energy should be transported. If we return again to f14 and ask how the transportation of water is done the answer is composed of two parts. Firstly we can answer by mentioning the means i.e. the components used to realize the functions, secondly we can provide a further elaboration by a description of the manner in which the means are used to obtain the transportation. It is seen that the description of the manner is given in terms of functions . Finally, we can also ask for the circumstances under which the transportation f14 can be done. These circumstances are derived from the two objectives O3 and O4. Thus we can say that the transportation can be done under the conditions that O3 and O4 are satisfied.

In diagnostic reasoning these types of explanation can be used to generate chains of arguments explaning why a function is disturbed on one of the levels. Possible causes for a disturbed transport f14 can accordingly be derived by searching the model in a downwards direction. The cause is then a disturbance of the pumping (PP) which again can be explained by a multiple of possible causes derived from the part-whole relation between the pumping aggregate and the elementary flow functions (f15, f16, f17, f18, f19, f20 and f21). Furthermore, the disturbance of f17 can be explained by a failure of the lubrication system to maintain the required oil flow specified by the objective O3. Alternatively the failure of f17 can also be explained by a failure to maintain water level in the expansion tank above the limit specified by the objective O4.

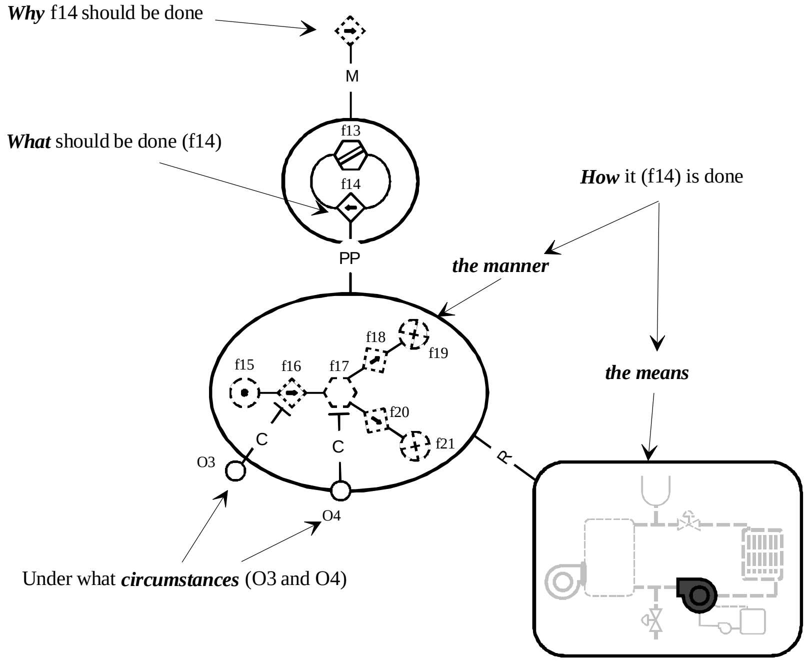

Fig. 4. MFM support different types of explanations

Due to the representation of the means-end and part-whole relation in the MFM model, a problem that is difficult to solve by reasoning in the physical topology is transformed into a manageable problem. Information may be added to the model about probable failure modes for the different subsystems of components in order to make the search more efficient. This information is intentionally not included in the MFM model because it is regarded as a base representation that can be extended with additional information depending on the problem to be solved. Larsson(1996) developed a knowledge based system for diagnosis that demonstrates the representational power of MFM for diagnostic problems.

MFM is also suitable for solving planning problems. In such problems the model could be searched in the direction from the means towards the end and from the parts towards the wholes or in the other direction depending on the chosen planning strategy. Larsen(1993) and Souza(1996) developed knowledge based planning systems demonstrating the efficiency of MFM for planning of start-up procedures for power plants.

A main advantage of using MFM for diagnosis and planning is the limited complexity of the reasoning processes required. This makes MFM attractive for the design of human-machine interface for supervisory control. However, it should be noted that this advantage, as usual, is not gained without a cost. The building of an MFM model is a complex process. The development of strategies for model building is therefore an important challenge for future MFM research.

2.6 Roles and Contexts

The producer product (PP) and the mediate (M) relations interrelate two levels of abstraction. The shift in abstraction when changing the focus from the producer to the product node or from the mediator to the mediated in an MFM model implies interesting shifts in point of view and representation of the role of plant components or materials. These aspects are not explicit in the graphical representation of MFM but can explained through the example as shown in Fig. 5. It is seen that in the context of producing momentum (pumping) the pump has the role of being the agent and the water is the object of action. These roles change when we change the context to ’water circulation’. This shift involves, according to the semantics of the PP relation, a change of emphasis from describing the process producing the result to describing the result (product) of the process. The process is the pumping and the product is the water being transported. In this new context, the water has still the role of being an (transportable) object of action but the transporting agent is now the subsystem ’pump and piping’ realising the transportation. Now, following the relation of mediation the circulating water enters a new role of being the agent and the energy being the object of transportation. The mediation relation then involves the ability to occupy two roles at the same time and a condition of covariation (mass flow rate and energy flow rate are both dependent on velocity).

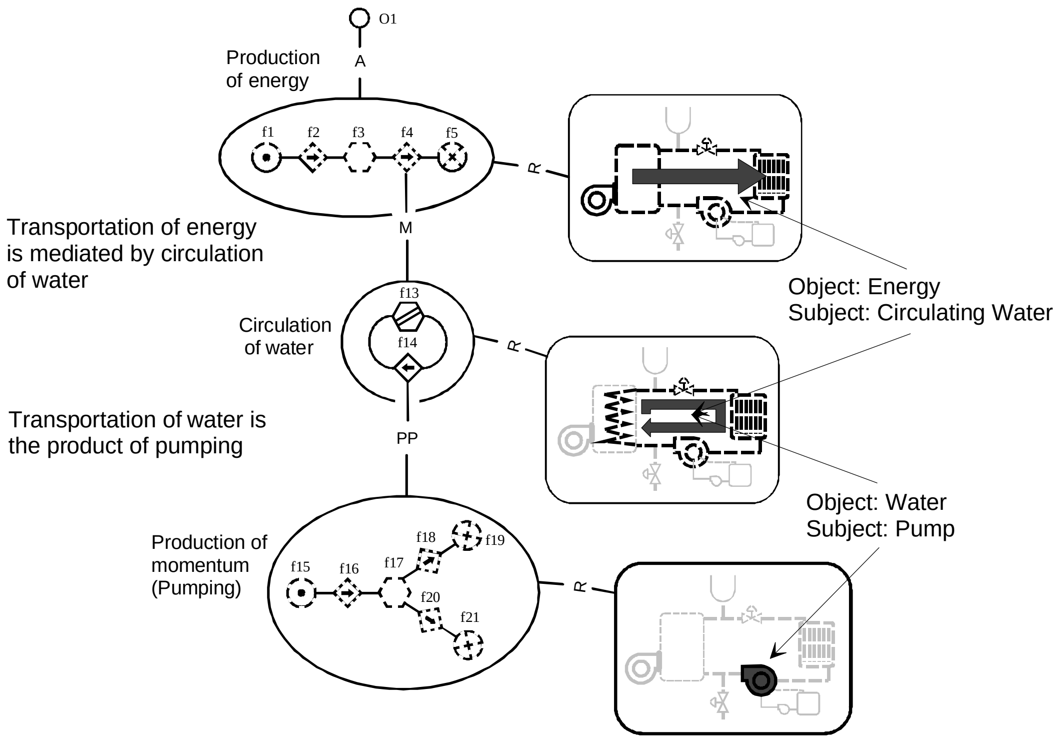

Fig. 5. The roles of materials and plant components depend

on the context of functions and objectives.

It is realised that an understanding of the working of the central heating system is highly dependent on the ability to manage these shifts in context and the associated changes in levels of abstraction. Furthermore, this understanding would be necessary for the solution of diagnostic problems. MFM provides a modelling framework for designing supervisory systems that enable the operator to manage these shifts in context and point of view.

2.7 Intervention

Multiple points of intervention that potentially can be used to realise a given intention can also be derived from an MFM model. An operator of the central heating system having the intention to increase the transport of energy (f4) from the boiler may increase the circulation of water if intervention is possible on that level (f14) e.g. by commanding a flow control system. Alternatively, the operator may intervene on the level of pumping by e.g. increasing the power supplied to the pump (f15). Further decision on which flow function to intervene requires actually more information about causal relations than the model provides at present. Representations of causal relations in MFM were introduced by Fang(1995) and are currently under development. It is seen that the derivation of poi nts of intervation is based on the mediate and the producer-product relations in the model that combine into causal paths.

2.7.1 Function enablement and initiation

MFM models include a distinction between enabling and doing introduced by the condition relation. A condition relation relates a function F with an objective O that describes a condition for enablement of the function. The function may have several conditions and it is assumed that all these conditions, each individually necessary, together are sufficient for the enablement of the function. However, satisfying the condition (fullfilling the objectives) is not sufficient for realising the function. As an example: The lubrication of the pump enables the transport of energy in the pump (f16) from the energy supply to the shaft, but does not initiate the transportation i.e. makes it happen. The power supply should be turned on. The intiation require an intervention on f15, causing the energy to be transferred (due to the construction of the pump). The causal relations between the functions implied here are not included in the model. This distinction between enablement and initiation is a significant feature of MFM models and is important for reasoning about startup situations and, more generally, about the role of support subsystems.

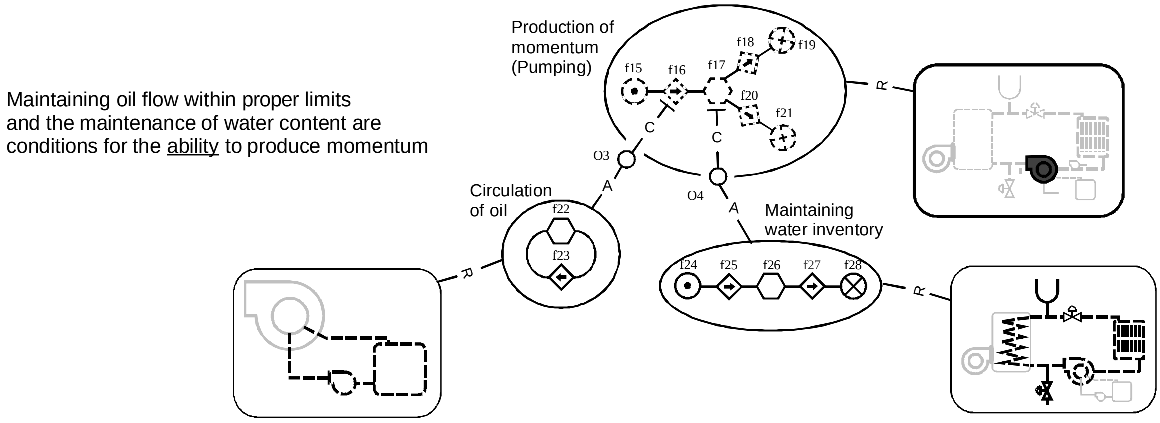

Fig. 6. Condition relations in MFM imply a modal distinction between ability and doing

3 DISCUSSION

MFM contributes to the conceptual design of displays for supervisory control by providing a methodology for representing industrial plant on several levels of abstraction. It should be recognized that MFM extend the conventional wisdom of representing industrial plants by a set of interconnected components. In such descriptions only components and their interconnections are represented and they are therefore only suited to reason about topology and disturbances that have local effects. MFM introduces additional levels of description which are better suited for understanding the implications of more global situations where several subsystems interact. The MFM model is not only depending on knowledge of the physical structure of the plant but also on the goals and intentions of the plant designer.

One of the advantages of using MFM for solving diagnosis and planning tasks is the limited complexity of the reasoning processes required. This is one of the reasons why MFM is attractive for the design of human-machine interface for supervisory control. Furthermore, the model organises plant knowledge in a way that is very suitable for planning the information content of a presentation system with multiple information windows. It should be stressed that MFM does not address the important problem of how to present or visualise the information. Duncan and Prætorius(1989) and VanPassen(1996) developed and tested displays visualising information by the use of MFM symbology. However, even though these studies indicated that MFM symbols may be used in visualisation, it is still an open question what means of presentation should be used to present abstract concepts like functions, objectives and goals. Even though one of the attractive features of MFM is its graphical format, it may be more efficient to communication abstract notions through a textual dialogue. A systematic approach to the visualisation problem is proposed by Pedersen and May (1998).

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REFERENCES

Bisantz, A. M. and Vicente, K. 1994. *Making the Abstraction Hierarchy Concrete*. Int. J. Human-Computer Studies, Vol 40, 83-117.

Duncan, K.D., Prætorius, N. 1989. *Flow Displays Representing Complex Plant for Diagnosis and Process Control*. Proc. 2nd. European Meeting on Cognitive Science Approaches to Process Control, Siena, Italy, October 24-28.

Fang, M. and Lind, M. 1995. *Model Based Reasoning Using MFM*. Proc. of Pacific-Asian Conference on Expert Systems. Huangshan, May 15-18, China.

Greimas, A. 1966. *Semantique Structurale*. Librarie Larousse, Paris France..

Larsen, M. N. 1993. *Deriving Action Sequences for Start-Up Using Multilevel Flow Models*. PhD thesis, Servolaboratoriet (now Department of Automation), DTU.

Larsson, J. E. 1996. *Diagnosis based on Explicit Means-End Models*. Artificial Intelligence, vol 80, pp. 29-93.

Lind, M. 1994. *Modelling Goals and Functions of Complex Industrial Plant*. Journal of Applied Artificial Intelligence, Vol 8, 259-283.

Lind, M. 1999a. *Making Sense of the Abstraction Hierarchy*. Proc. Conference on Cognitive Science Approaches to Process Control, CSAPC´99, Villeneuve d'Ascq (France), 20-24 September.

Lind, M. 1999b. *Actions, Functions and Failures in Dynamic Environments*. Working Notes, Department of Automation, DTU and Centre of Human Machine Interaction, RISØ .

Norman, D. A. 1986. Cognitive Engineering. In:Norman, D. A. and Draper, S. W. (Eds.*) User Centered System Design: New Perspectives on Human-Computer Interaction. Hillsdale, NJ. LEA (pp. 31-61).*

Pedersen, C. R. and May, M. 1998. *Visualisation in Process Control*. Proc. 7the IFAC Symposium on Analysis, Design and Evaluation of Man-Machine Systems. Japan.

Petersen, J. and Lind, M. 1998. *Considerations on Agents and Objects in Multilevel Flow Modelling*. Proc. EAM'98, Valenciennes, December 14-16, 1998.

Poulsen. H. 1999. *Actant model of an extraction plant*. Reliability Engineering and Systems Safety. 64, 2, pp 225-240.

Rasmussen, J. 1986. *Information Processing and Human-Machine Interaction*. North Holland, New York.

Rasmussen, J., Pejtersen, A. M. and Goodstein, L. P. *Cognitive Systems Engineering*. John Wiley, New York.

Soza, E. and Veloso, M. 1996. *AI planning for a Supervisory Control System*. Proc IEEE International Conference on Systems, Man and Cybernetics, China, October.

VanPassen, R. 1996. *Visualization of Process Means-Ends Hierarchies for Advanced Man-Machine Interfaces*. Universität Gesamthochschule Kassel. Final Report project ERBBRE2CT943085.

VanPassen, R. and Wieringa, P.A. 1999. *Reasoning with multilevel flow models*. Reliability Engineering and Systems Safety. 64, 2, pp 151-165.

VonWright, G. H. 1963. The Logic of Action: A Sketch. In: Rescher, N. *The Logic of Decision and Action*. University of Pittsburgh Press, Pittsburgh.

Relation	Symbol	Explanation
Achieve	A	(A) represents the relation between an objective (end) and the function or systems of function (the means) that are used for its achievement.
Achieve by control	A-C	(A-C) represents a control systems as a mean for achieving an objective.
Condition	C	(C) represents a relation between a function and an objective that should be satisfied in order to enable the function.
Goal-Objective	GO	(GO) represents the relation between a goal and its corresponding technified objective.
Goal-Subgoal	GSG	(GSG) represents the relation between a goal and a subordinate subgoal.
Producer-Product	PP	(PP) represents the relation between a process that result in (produces) a product (state or activity) that again serves another function in the system.
Mediate	M	(M) represents the relation between an object of action and the system mediating the action.
Function Connection	—	(FC) represents a relation between two functions meaning that they relate to the same goal perspective or that they share objects
Realize	R	(R) represents a relation between a function and the physical components or subsystems that implements the function.

Table 1. Symbols and short explanation of the MFM relations

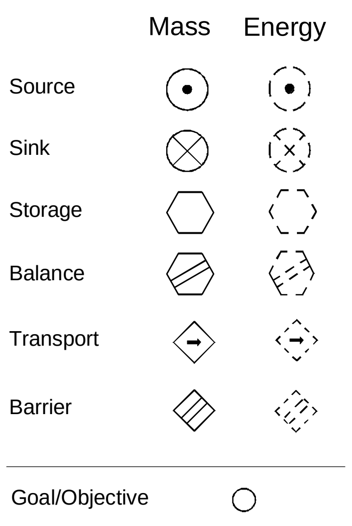

Table 2. Flow function concepts and symbols