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Representing Operational Modes for Situation Awareness

Denis Kirchhübel[1], Morten Lind[2] and Ole Ravn[3]

[1]PhD Student, Department for Electrical Engineering, Technical University of Denmark
[2]Professor emeritus, Department for Electrical Engineering, Technical University of Denmark
[3]Associate Professor, Department for Electrical Engineering, Technical University of Denmark

E-mail: dekir@elektro.dtu.dk

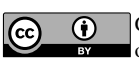
Abstract. Operating complex plants is an increasingly demanding task for human operators. Diagnosis of and reaction to on-line events requires the interpretation of real time data. Vast amounts of sensor data as well as operational knowledge about the state and design of the plant are necessary to deduct reasonable reactions to abnormal situations. Intelligent computational support tools can make the operator's task easier, but they require knowledge about the overall system in form of some model.

While tools used for fault-tolerant control design based on physical principles and relations are valuable tools for designing robust systems, the models become too complex when considering the interactions on a plant-wide level. The alarm systems meant to support human operators in the diagnosis of the plant-wide situation on the other hand fail regularly in situations where these interactions of systems lead to many related alarms overloading the operator with alarm floods. Functional modelling can provide a middle way to reduce the complexity of plant-wide models by abstracting from physical details to more general functions and behaviours. Based on functional models the propagation of failures through the interconnected systems can be inferred and alarm floods can potentially be reduced to their root-cause. However, the desired behaviour of a complex system changes due to operating procedures that require more than one physical and functional configuration. In this paper a consistent representation of possible configurations is deduced from the analysis of an exemplary start-up procedure by functional models.

The proposed interpretation of the modelling concepts simplifies the functional modelling of distinct modes. The analysis further reveals relevant links between the quantitative sensor data and the qualitative perspective of the diagnostics tool based on functional models. This will form the basis for the ongoing development of a novel real-time diagnostics system based on the on-line adaptation of the underlying MFM model.

1. Introduction

Modern complex production plants are becoming increasingly demanding due to the distributed nature of the control system and increased requirements of safe and efficient operations. While every component of a system may be within its operating margins, undesired interaction betweens certain component states can accumulate to catastrophic situations. It is therefore important to not only consider single components but the combination of all interrelated parts of a complex system. In order to cope with the complexity of systems different perspectives are relevant to represent the interactions within the system beyond different time scopes and levels of detail with regards to structure, function and behaviour (SFB). [1]



For robust and fault-tolerant systems tools, such as structural analysis have been developed to model the interrelations between subsystems and enable failure diagnosis.[2] However, for plant-wide diagnosis industrial plants rely mostly on the experience and diagnostic skills of human operators. The operators establish the state of the plant based on alarms generated for possibly abnormal states indicated by sensor readings.[3] While the concepts for fault-tolerant systems are used on the level of components or subsystems, the majority of improvements for alarm systems reviewed by Wang et al. [3] disregard the process knowledge and rely on data driven methods. This can be related to the problem of high complexity of an overall plant described by Venkatasubramanian et al. [1], especially considering the extension and replacement of components throughout the live span of an industrial plant.

One way to overcome the lack of process knowledge incorporated in alarm systems and the high complexity of mathematical descriptions is presented by the SFB approach. SFB modelling provides an abstraction of the system, that can be used to analyse and diagnose the system based on the interaction of different structures, functions and purpose. One form of SFB modelling is Multilevel Flow Modelling (MFM), which provides a modelling language as well as a diagnostics tool for qualitative cause consequence reasoning to identify how abnormal states propagate through the system. [1, 4]

As addressed by hybrid systems modelling certain conditions or events in the control system lead to different states of a system by changing its behaviour.[2] On a plant-wide level such discrete states can be generated by different configurations of subsystems because of operational procedures or to efficiently use redundant systems. Such configurations can be considered as operational modes of a plant. While operational modes have been the subject of MFM related research [5, 6], no consistent and easy way of modelling these modes has been proposed. The research of operational modes of a nuclear power plant by Lind et al. [6] showed that each mode can be represented in a distinct MFM model with regards to functions and goals of the mode. Those distinct models, however, disregard the operational knowledge on how modes are interconnected and what the boundaries of the modes are with respect to operation procedures.

This paper describes a new way of interpreting control functions and relations as part of the operational knowledge included in MFM. Similar to hybrid systems modelling discrete events are identified that determine boundaries of a mode and facilitates the incorporation of operational procedures in MFM models through the generation of interpreted models that express implicit knowledge. The proposed interpretation reveals, how the constraints for validity of the qualitative model are closely linked to the quantitative aspects of real-time sensors or alarms and will form the basis of the ongoing development to link MFM modelling and artificial intelligence approaches to create a novel plant-wide on-line diagnostics system based on the cause and consequence reasoning in MFM.

In section 2 different approaches to plant-wide on-line diagnostics are outlined and the basic concepts of modelling and reasoning in MFM are briefly described as well as the state of the art with regards to operational modes, especially in MFM. Section 3 describes the concepts for linking control functions and modes based on discrete models of a start-up procedure. In section 4 the mode models generated with the proposed interpretation are evaluated. Finally the conclusions drawn from this conceptual work and the future development based on this concept are outlined in section 5.

2. State of the art

The study of Venkatasubramanian [1] describes how the computerization of industrial processes has lead to robust and fault tolerant control of components and that artificial intelligent approaches have been shown to enhance the maintenance scheduling and degradation diagnostics for specific applications. While these systems help improve the performance of a specific components most diagnostics systems are based on physical or statistical models of the system

and would become too complex if all, possibly undesired, interactions between the components of the system are to be considered. From a system safety perspective the robustness of automated system parts does not make the entire system resilient to failure. One weak point is presented by the vast amount of information that a human operator needs to process, which makes the assessment of an emergency situation difficult, especially given the limited time frame for appropriate reaction. [1]

Modern industrial plants are equipped with a large number of sensors and control systems that can generate alarms to alert the human operator to a possible failure. With the increasing number of distributed control systems the number of alarms in a plant increases as well. While statistics driven analysis of plant data can aid auditing processes and filtering of excess alarms, the propagation of abnormal states due to the interconnections of components in the plant leads to alarm floods that overload the operator and make it hard to identify the origin of the failure. While alarm floods have been investigated by different groups, there is no established applicable solution to deal with alarm floods. Identifying related alarms that lead to alarm floods requires a system with knowledge about the interactions of different components in the plant. [3]

Incorporating the expert knowledge of human operators and plant designers into a support system can aid the decision making process by identifying root causes and planning appropriate reactions. To implement this approach rule based expert systems have been developed. These system can analyse a situation and infer procedures based on rules that are deducted from the expert knowledge of operators. A drawback of such systems is the domain specific nature of the expert knowledge and thus the narrow applicability of one such support system. [7] A more generic approach to communicating and evaluating expert knowledge is presented by functional modelling (FM). FM frameworks commonly abstract a system as a set of desired behaviours of the whole system or as a combination of functions of its components. This abstraction provides a general overview of the entire system by interconnecting different knowledge domains. The schematic representation of FM can facilitate computer reasoning about the entire system. [8]

The functional modelling language of MFM was originally developed as analysis tool to assist human operators in identifying and handling unknown operation situations [9] and to support the design of human-machine interfaces [10]. MFM has been demonstrated as a valuable tool to represent operational knowledge about processing plants in a range of technological areas in a machine readable form. Among others MFM is used for operator support scenarios in research projects such as the OECD Halden Reactor Project[4], where the MFM framework is applied for cause and consequence reasoning about abnormal states of the plant. This kind of reasoning allows the operator to relate connected alarms and react more efficiently with a focus on the root causes and preserving essential system functions.[4] Another branch of MFM has focused on deriving fault trees and failure mode analyses[11] and possible counter actions[12] based on MFM.

2.1. Multilevel Flow Modelling

A MFM model is a hierarchical decomposition of goals to be achieved by certain functions of the system, as well as a part-whole decomposition of a system function into basic material and energy flow functions. MFM provides a graphical modelling language with symbolic representations of these basic flow functions and the relation between functions and objectives of the system. Figure 1 shows the defined MFM primitives. In a MFM model the flow function primitives are usually used in several flow structures. The functions are connected by influence relations inside a flow structure and by means-end relations across decomposition levels representing the contribution to another function or an objective.

Besides the analysis and representation of function, MFM can be used to reason about the system performance. The reasoning is established in terms of qualitative performance of each function and the propagation of abnormal performance states by the relations of one function to

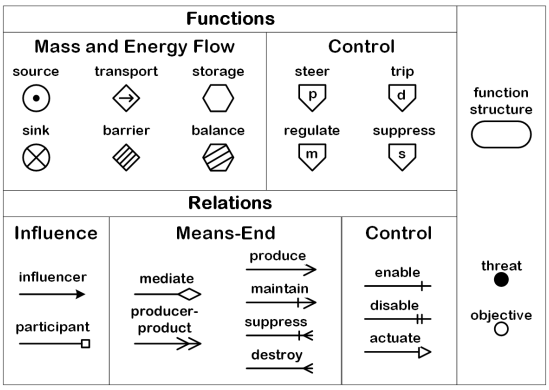


Figure 1. Basic MFM concepts[4]

Table 1. MFM control functions[13]

Intention	action	symbol
produce	$[\neg pTpI\neg p]$	p
maintain	$[pTpI\neg p]$	m
destroy	$[pT\neg pIp]$	d
suppress	$[\neg pT\neg pIp]$	s

another. Table 2 shows the underlying equations and the qualitative states that form the basis for the reasoning system. Cause and consequence inference rules for the possible combinations of flow functions and relations have been detailed by Petersen[14] and most recently elaborated on by Zhang et al. [4, 15]. The reasoning considers the abnormal states of functions in the way alarm systems commonly represent abnormal sensor readings as high (high-high) or low (low-low). Based on the interactions of the function primitives the propagation of abnormal states can be inferred in both forward (consequence) and backward (cause) direction.

Table 2. Underlying equations, constraints and failure states of MFM flow functions[4, 14]

Flow function	Balance equation	State Constraints	Abnormal states
Transport	$F_{in} = F_{out} = F$	$F_{low} \leq F \leq F_{high}$	low low, low, high, high high
Storage	$\Sigma F_{out} = \Sigma F_{in} + dV/dt$	$V_{low} \leq V \leq V_{high}$	low low, low, high, high high
Source	$\Sigma F_{out} = F_{unknown} + dV/dt$	$V_{low} \leq V \leq V_{high}$	low low, low, high, high high
Sink	$\Sigma F_{in} = F_{unknown} + dV/dt$	$V_{low} \leq V \leq V_{high}$	low low, low, high, high high
Balance	$\Sigma F_{out} = \Sigma F_{in}$		sourcing, leak, block
Barrier	$F_{in} = F_{out} = F$	$F = 0$	leak

In addition to the fundamental flow functions and objectives, MFM allows the modelling of control functions as means of intervention. Lind [13] introduced the action notation for the control functions in table 1. This notation uses the temporal operator T and an operator I, where the state after T is achieved by the control intervention instead of the state after I which the system would move to without intervention. These control functions are concerned with the functional meaning or intention of the control design e.g. to keep a flow in an heat exchanger steady rather than a specific realization of the controller. A control function is normally connected to an objective that represents the target function to be controlled. The actuate relation connects the control function to the functions that controlled to achieve that target, e.g. a pump is actuated in order to maintain a certain water level in a tank. Zhang et al. [16] point out that the purpose of a control action can be modelled for automated as well as manual intervention. Control functions in MFM are thus a way of extending the model with expert knowledge about the way a plant is operated.

2.2. Operational Modes

In the context of diagnosis and faults-tolerant control a similar concept to operational modes is reflected in the hybrid nature of fault-tolerant systems. Fault-tolerant control reconfigures the structure and parameters based on logic as reactions to discrete events, such as faults in the system. The different configurations can be represented as distinct states, exposing a specific behaviours based on the configuration of the control. The evolution of these states can be described e.g. by Petri nets or similar representations. The combination of continuous model for each state and the discrete events limiting the validity of a state is represented in a hybrid systems model. In the hybrid model the discrete events limiting a state are described as constraints on specific system variables. [2]

Operational modes as such have been investigated by Lind et al. [6] with regards to their representation in MFM. Operational modes can occur on two different levels of abstraction: as a relation of objective to function, or as a relation of function to physical structure. On either abstraction level modes can be defined both ways, as a selection of means to achieve a constant end, or as a selection of ends that can be achieved by the same means. Zhang [4] elaborates that this classification is relevant to assess the operability of plant as indication for necessary mode shifts, e.g. configuration changes. Such a configuration change could be between redundant systems, changing the physical structure (means) to achieve the same function (end). Equally a configuration change could be opening a valve (means) thus changing its function (end) from blocking to transporting. Analogously a certain set of functions could serve different objectives, depending on the mode, or vice versa. However, the boundaries of one operational mode are at present not represented in the MFM models.

Inoue et al. [12] use MFM models to generate plausible operation procedures in unknown emergency situations. In order to generate these procedures knowledge about possible, and possibly undesired alternative functions of physical components has to be considered. This kind of situation relates directly to the function to structure mode definition by Lind [6]. Gofuku et al. [11] introduced operational information in addition to the MFM models to include the required knowledge. For the context of operational modes the most relevant aspects of operational information are the component behaviour and operation knowledge.

Component behaviour knowledge refers to the plausible behaviours of a physical structure and their functional representation. Operation knowledge represents the possible interventions and the functional influence of the intervention. Operation knowledge is essentially part of MFM models by including manual as well as automatic interventions in the modelled control functions [16]. The other aspects of operation information are not as clearly defined in the MFM Framework as the additional information Gofuku et al. [11] describe. Alternative behaviours of components have been widely disregarded by the MFM framework, since a MFM model is used to represent intended behaviour [4].

3. Operational modes and control

In order to illustrate the concepts to consistently represent operational modes in MFM the discrete models of two modes in a start-up procedure of a generic power plant are analysed.

To get the power plant up to operation the first step is filling the boiler drum and piping with water. Figure 2 shows the active material flow path during this stage of the start-up procedure: Water is pumped from a reservoir into the boiler drum and the ventilation valve is left open to allow air to escape from the steam piping at the output of the boiler. The goal of this stage is to fill the drum to the required water level before the steam production can be initiated. The MFM model shown in figure 4 reflects the described material flow with the function primitives of MFM. In addition to the intended material flow, the closed off parts of the system, namely the economizer recirculation and the recirculation of steam through the condenser are included as barriers in the MFM model. Including these barriers allows to consider faulty valve behaviours

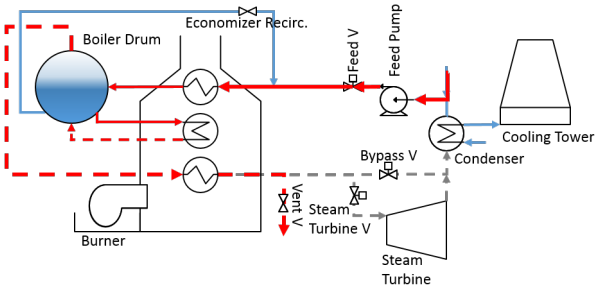


Figure 2. Filling of a generic power plant

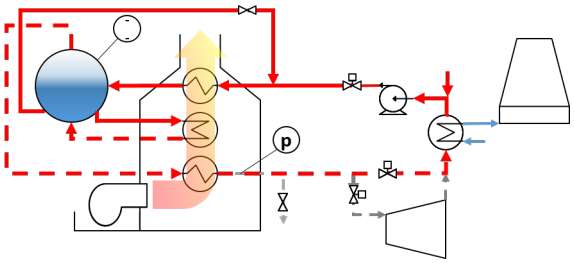


Figure 3. Pressurizing of a generic power plant

in the reasoning. The control of the water level in the drum by actuating the feed pump is reflected by the control flow structure, specifying the intention of the mode as producing the required water level.

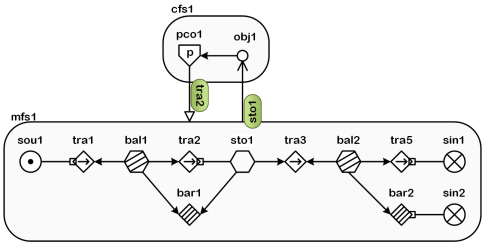


Figure 4. MFM model of filling

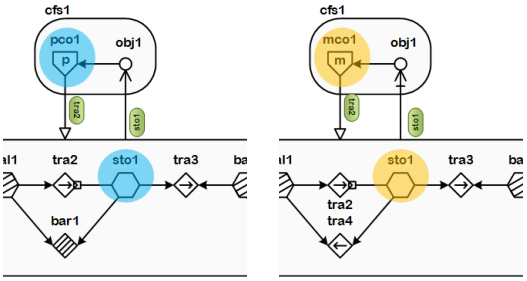


Figure 5. Mode change indicators and corresponding control function in subsequent modes

Before the steam turbine can be operated to produce energy, pressurized steam has to be generated in order to provide enough energy to convert in the turbine. After steam has been generated is superheated and recirculated to raise the pressure in the system. The MFM model shown in figure 6 is developed according to the active components in figure 3. The mass flow structure of fuel and air in the burner is included in the model. The heat from the burner enables the introduction of the energy into the system as represented by the energy flow structure. In this mode the control of the temperature and pressure in the steam piping actuates the flow of steam through the condenser to raise the thermal energy in the steam piping. The overall goal of this stage of the operation procedure is to generate the necessary steam pressure to be able to spin up the turbine.

Comparing the functional representation of corresponding elements across the two modes reveals that the goal and end-point of these modes are related to the control actions, more specifically the end point of produce action. While the control function remains present in subsequent modes, the associated control action changes e.g. from produce to maintain as shown in figure 5. The representation of valves that can either be closed or opened to change the physical configuration of the system is either a barrier or as a transport function.

Besides valves as a means of changing the system configuration, specific components, like the burner, can be enabled or disabled. This behaviour is reflected in the way that a disabled components function does not contribute to the function of the system and is thus not considered in the model.

The concepts described in the further part of this section have been developed based on these

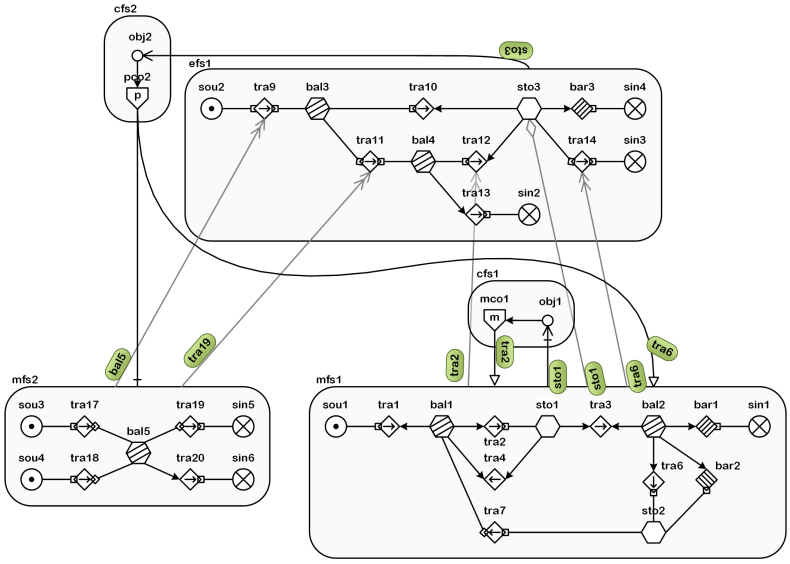
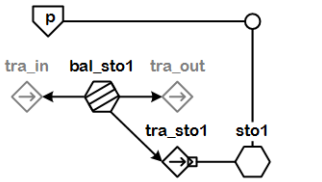


Figure 6. MFM model of pressurizing

Table 3. Intended behaviour of a storage with produce controller



$$\Sigma T_{out} = \Sigma T_{in} - T_{sto1}$$
$$dV/dt = T_{sto1} > 0$$

findings and present a pre-processing of a designed MFM model into an interpreted model. The interpreted models are intended to work with the established cause and consequence reasoning based on MFM.

3.1. Control sequence

The distinct models for the start-up modes have shown, that the end-point associated with the overall objective of one mode is linked to producing a certain storage level in order to prepare the system for the next operational mode. This objective of producing, thus increasing, a certain storage level can not be inferred from the underlying definition of a storage shown in table 2. According to the definition of a storage the only constraint is on the level of the storage.

In order to reflect the intended aspect of a defined inflow in order to increase the storage level, the function of the storage has to be considered to act like a sink. The interpretation of a storage to be produced with a defined inflow is shown in table 3. By explicitly including a transport function the inflow can be constraint with relation to the quantitative values in the physical system. Figure 9 shows the cause reasoning output for a high level in sto1 of the fill mode represented in figure 4. Considering the states as indicators rather than faults this can be interpreted as possible paths to achieving the goal of this mode: The storage level can be raised by generating a high inflow into the system as well as by keeping the outflow low (no water should leave through the vent valve).

Similar constraints can be introduced for all control functions in MFM. Based on the action schemes defined for the MFM control functions there is an inherent sequence of the control functions in relation to operational modes, as shown in figure 7. Reasoning about the validity of one mode can be based on the quantitative constraints linked to the intended behaviour of a controlled storage. A breach of either of the constraints on the storage level or the timely change thereof, represented by the in or outflow, indicates a necessary configuration change or a failure of the controller.

Analogous to the concepts of fault-tolerant control the breach of the constraints can be interpreted as a discrete event that leads to a change in the system configuration. The discrete states of a fault-tolerant system as well as the designed operation modes of the overall plant can be defined and reasoned about as exemplified in figure 8. An important difference, however,

is the fact that the model for each mode expresses the boundaries it is designed for explicitly, as opposed to the continuous models in hybrid systems where assumptions for a mathematical model are implicit in the model and expressed explicitly only by the separately defined events.

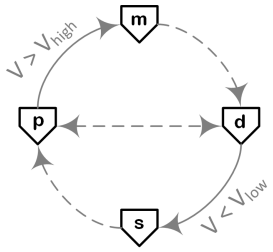


Figure 7. Implicit (solid) and deliberate (dashed) control function sequence throughout modes

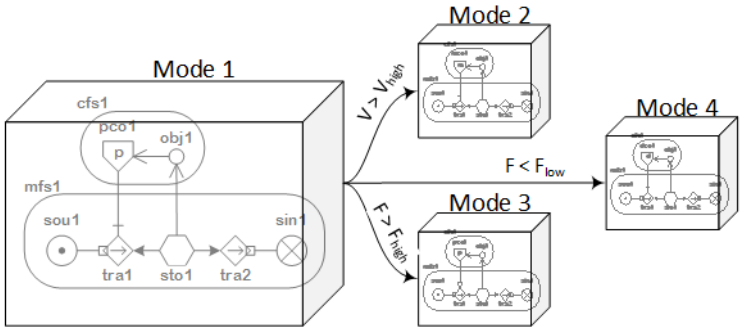


Figure 8. Possible mode transition events with a single produced storage

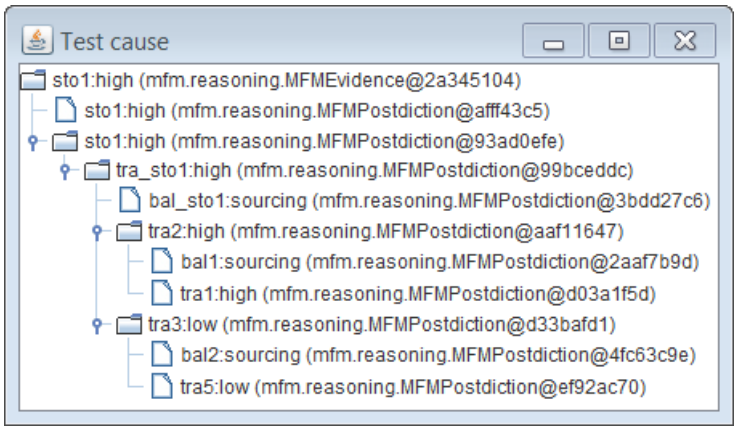


Figure 9. MFM based cause tree for high water level in the generic powerplant during filling

3.2. Modelling configuration

The difference in the configurations considered in the distinct models of the power plant start-up can be represented by transport or barrier functions reflecting the state of a valve. As described in the previous section the reasoning about operational modes is closely related to the intention represented by control functions. Consequently, the control relations are explored as a means of representing configuration in MFM.

MFM defines three control relations, where the enable and disable relation directly correspond to the two complementary states a configuration valve can have (open or close). However, the functional representation of a configuration valve can coincide with the function of a continuously actuated control valve. The enable and actuate relations are thus interpreted to reflect the normal function, while the disable relation is interpreted in the preprocessing to reflect a closed valve or deactivated component.

The analysis of the start-up procedure revealed that a closed valve does not only affect the MFM function representing it, but also propagates through the means-end relations, specifically

the mediate and producer-product relations. In effect, if a transport function as producer is interpreted as barrier, the transport function, that is the product, also has to be interpreted as a barrier.

Using the concepts for interpretation proposed here, allows for a mode to be represented by a set of control functions that reflect the objective of the mode and a set of control relations to reflect the configuration. This set can be defined as additional information for a MFM model as reference, thus adding a two step process to generate the interpreted models for the MFM based cause and consequence reasoning: The first step is model generation, that adapts the reference model to contain the control functions and relations for the respective mode. The second step is the interpretation of the control relations and the functions to represent the intended behaviour of the mode in an interpreted model that is subsequently used for the reasoning.

4. Generating models

By joining the MFM model of all modes a reference model to accommodate all modes can be derived. This model essentially reflects all possible flows as they could for example be found in a piping and instrumentation diagram. An exemplary combined model for the generic thermo-electric power plant is shown in figure 10

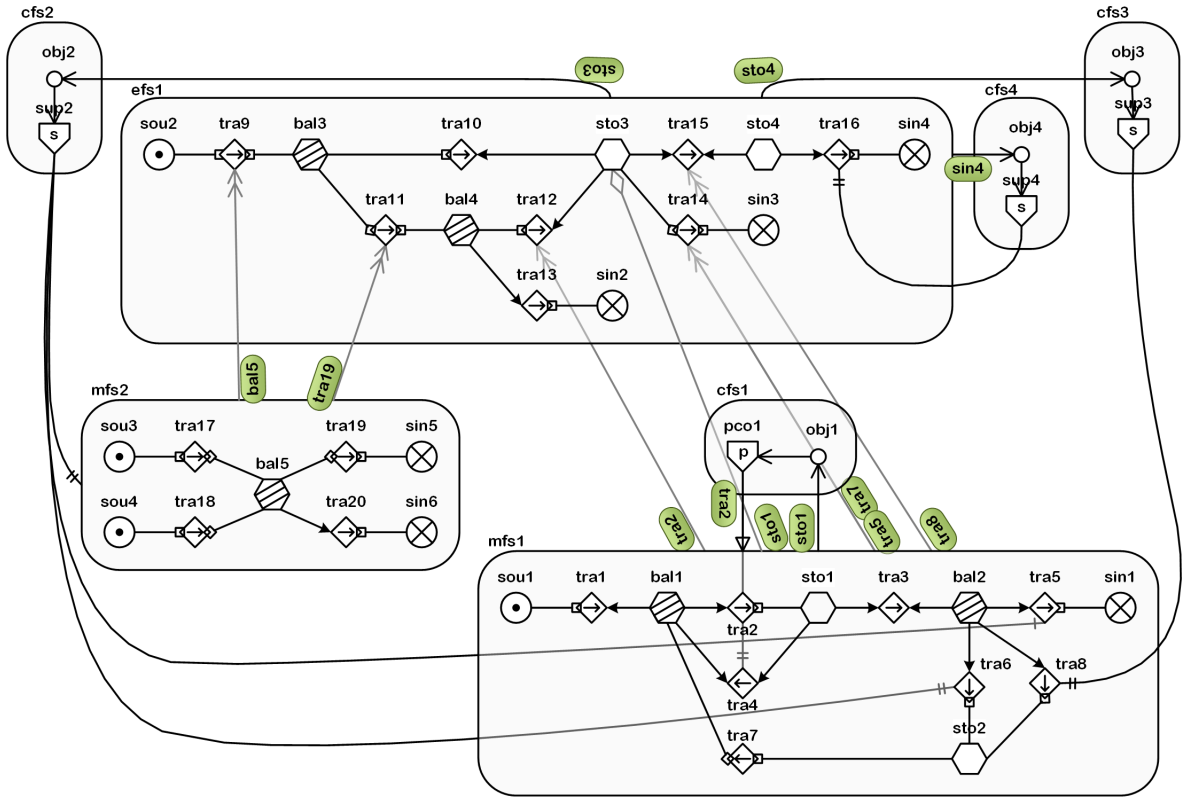


Figure 10. Reference model (fill mode) for a generic thermo-electric power plant

Using the proposed interpretation concepts the MFM representation for a specific mode can be generated. For the sake of readability the explicit modelling of the intention of control has been left out of the interpreted model for filling shown in figure 11. Comparing this model to the discretely modelled representation of the same mode in figure 4 there are some obvious differences.

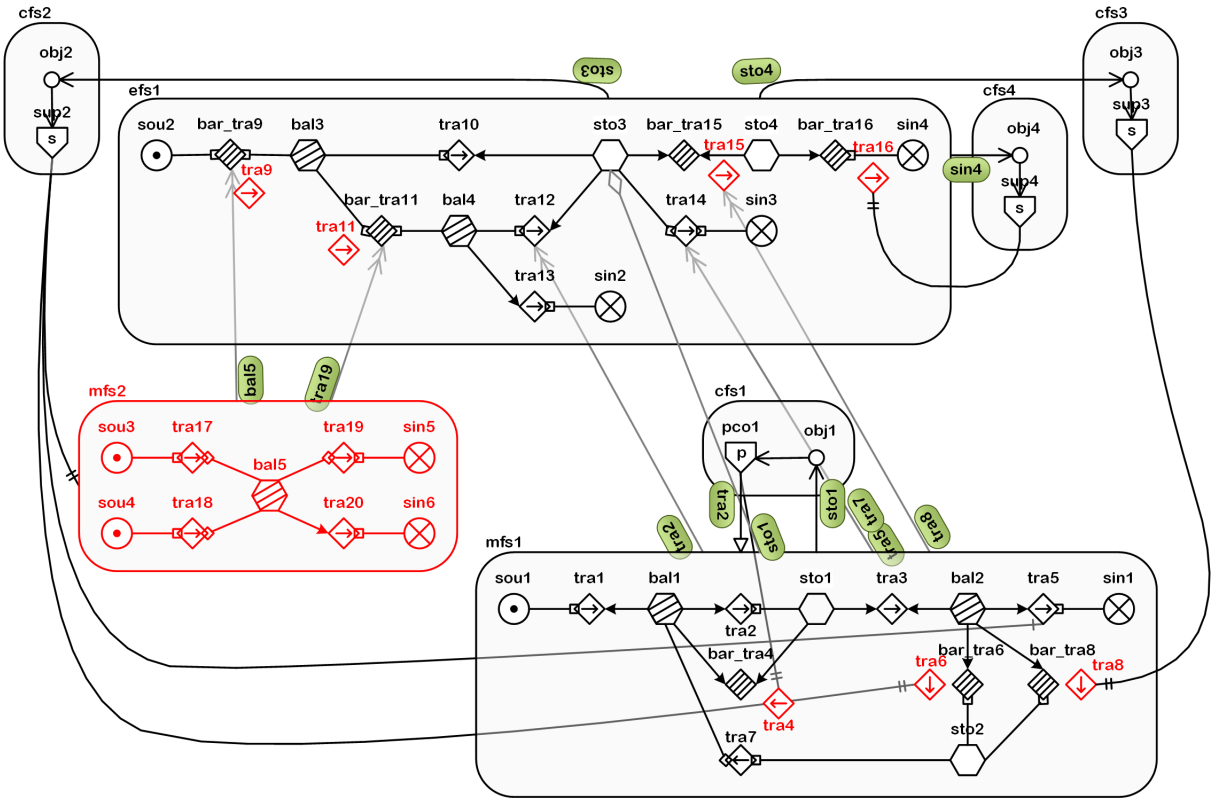


Figure 11. Meta-model of the fill mode

The central mass flow structure of the discretely developed model for the filling mode did not contain the recirculation of water through the condenser, since that part of the system is not part of the functional scope of the mode. However, the functional information is fundamentally the same, given that the barrier at the output of the discrete model is reflected more in detail by the two barriers in the recirculation.

The energy flow, while not relevant to the function of this mode, is represented in the interpreted model. A detailed inspection of that energy flow reveals, that there is no intended energy flow: From the source in the energy flow only barriers connect to the other functions and the two storages are connected to suppress control functions, thus acting as balances.

5. Conclusion

Functional modelling can provide the framework for representing process knowledge for a range of engineering applications. Incorporating such knowledge in a reasoning systems enables the creation of operator support tools that can help diagnosing the current state of a complex plant and provide guidance for reasonable reactions. This kind of plant-wide diagnosis is believed to be capable of relieving the load of alarms operators are confronted with by identifying connected alarms and thus yielding more meaningful information. MFM presents such a functional modelling framework with an established reasoning system for cause and consequence diagnostics.

In this work the distinctive elements of operational modes and the boundaries of each mode have been investigated with regards to functional modelling. Based on the analysis of distinct functional models for a start-up procedure concepts for the consistent representation of operational modes in MFM are proposed. These concepts facilitate the modelling of operational

modes in MFM by using a common reference model as basis for the generation of specific mode models. The common model can be derived from existing engineering documentation, such as piping and instrumentation diagrams, and thus simplifies the modelling process in MFM.

6. Future work

The proposed interpretation of the intention of each mode provides the means of linking the models for specific configurations to the real-time environment equipped with sensors. In the development process for a complete real-time diagnostics system based on MFM these concepts will serve as the basis for dynamically adapting the functional model to the actual state of the plant. An important element of this is to provide the rule system with knowledge about manual and automatic intervention points in the plant and their possible functions, as it is realized through the control relations in the proposed concepts.

The future effort in this field will be directed to the application of machine learning approaches to facilitate the identification of failure states from real-time sensor data, as well as the consolidation of the MFM based reasoning to enable on-line adaptation of the model to reflect the current state of the system. The goal for this project is to provide a novel kind of diagnostics system, that incorporates the operational knowledge and enables an organised representation of the state of a plant by identifying relevant failure paths from the on-line data.

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