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Toward Comprehensive Decision Support Using Multilevel Flow Modeling

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Abstract: The complexity of modern industrial plants poses significant challenges for the design of effective operator interfaces. Although established practices can significantly reduce the frequency of alarms, operators often cannot resolve the failure cascades commonly occurring during emergency situations. Automating control rooms by incorporating design and operation knowledge about the systems can significantly improve operator efficacy. Intelligent support systems should reduce the amount of information and provide more context to the operators. The operators focus should be shifted from information acquisition to taking informed decisions about mitigation steps. This contribution gives a brief review of the development of Multilevel Flow Modeling (MFM) and its application to provide operators with decision support and situation awareness, focusing on implementations directly utilising the knowledge represented in MFM. Finally, current efforts toward a comprehensive intelligent human machine interface for operators are outlined.

Keywords: Human supervisory control, Decision support systems, Intelligent knowledge-based systems, Alarm systems, Reasoning, Fault diagnosis

1. INTRODUCTION

Operators controlling industrial plants mostly rely on the alarm system to detect offsets requiring an action. Alarm system should be maintained in a state that does not overload operators during normal operation. However, during emergency situations the connections throughout a processing plant frequently lead to cascades of true alarms overwhelming the operator by presenting alarm floods (Beebe et al., 2013). To deal with alarm flood situations, the relation between the occurring alarms has to be analysed and presented to the operators as concise as possible. An intelligent operator decision support systems guides the plant operators to the region of the plant where the cascade originated from and offer assistance on how to mitigate the situation (Rothenberg, 2009). A timely analysis and suggestions for counter-action can help operators drive the process back to normal operation.

In addition to established alarm management practices in industry, mostly data driven alarm analysis methods have been proposed to reduce the strain on operators in abnormal situations. However, incorporating design and operation knowledge into the operator support can help operators with further prognostic information and a more concise understanding of the situation and its consequences (Wang et al., 2016). The analysis of recorded incidents is an established tool to predict recurring critical situations, for instance Zhu et al. (2016) propose matching the patterns of previous alarm floods. However, these methods depend on reliable data records and the assumption that those critical situations occurred before. A combination of alarm records with connectivity information from plant documentation is shown by Schleburg et al. (2013) to support the alarm analysis where only little data is available. While the plant documentation provides information about the connectivity of components in the plant the nature and direction of causality between deviations is necessary for an accurate analysis of closely linked deviations (Yang et al., 2014). Besides the identification of causal relations between alarms (Larsson et al., 2006), knowledge about the process can be used to automatically generate mitigation procedures for the current situation (Gofuku, 2011).

| Level of Automation   | Acquisition | Analysis | Decision | Execution |
|-----------------------|-------------|----------|----------|-----------|
| Triggered execution   | 5 +         |          |          |           |
| Single solution       | 4           |          |          |           |
| Selected alternatives | 3 +         |          |          |           |
| Complete set          | 2 ◦ ◦ ◦ ◦   |          |          |           |
| No assistance         | 1 ◦ ◦ ◦ ◦   |          |          |           |

Fig. 1. Current (◦) and envisioned (+) level of automation based on Parasuraman et al. (2000)
Traditionally the level of automation at a plant-wide level is characterised by a large cognitive load on the operators who only get alarm and trend information from the human-machine interface without any context. Parasuraman et al. (2000) outline the trade-offs to consider to define the level of automation. Fig. 1 illustrates the current state of plant operation and the target for a meaningful operator support tool. The goal is to provide a comprehensive solution to reduce the loads on operators and to guide them in critical situations. Therefore, the processing tasks of identifying the situation from a multitude of alarms and continuous signals should be hidden from the operators. Instead, operators will be provided with a short list of the most likely situation analysis and provided with a complete set of tentative consequences to base their decision on. Finally, a set of relevant mitigation procedures will be generated based on the operators diagnosis.

Multilevel Flow Modeling (MFM) has been proposed as a modeling methodology for all aspects of operator support. The method was originally developed to represent designers’ and operators’ understanding of the process and it was gradually extended to provide a comprehensive causal representation of an industrial plant. MFM provides an abstract representation of the connected mass and energy flows in a processing plant as a set of functions. A MFM model explicitly includes the causality between the functions fulfilled by the process units. 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 each system function into basic material and energy flow functions. MFM provides a graphical modeling language with symbolic representations of these basic flow functions and the relation between functions and objectives of the system. (Lind, 2013) Similar to other graph models, like bond-graphs (Borutzky, 2010) or signed directed graphs (Yang et al., 2014), MFM captures the causal connections throughout the process. However, it also takes a more contextual approach by analysing the plant at the plant-wide level relevant to operator decisions in control rooms rather than the mathematical detail required for other applications.

As an intuitive example a simple 3 tank system is shown in Fig. 3. The mass flow in itself is only composed of the water source, transports between storages, and a sink. The participant relations toward the transports reflect that the set point of the valves is the only determinant of the flow with the exception of V2, which is determined by the level controller on tank L2. This example illustrates the readily understood syntax underlying all MFM models, where multiple flow structures are usually combined in a hierarchical manner supporting the overarching goals of the plant.

Based on the knowledge in an MFM model, intelligent systems can be developed to assist operators in assessing the state of the plant. The major aspects of intelligent operator support are alarm filtering, root cause analysis and identifying mitigation procedures. Concepts and implementations for each of these aspects are found in the literature. However, no complete system covering the whole range from alarming to mitigation suggestions has been presented to date. The following section outlines a chronology of the research aiming at the application of MFM for online operator support in one of the mentioned aspects. Finally, a conclusion of the past efforts and an overview of our current efforts at the Technical University of Denmark toward a comprehensive operator support tool based on MFM is given.

![Flow sheet](image1)

![MFM model](image2)

**Fig. 2.** MFM function primitives adapted from Lind (2013). Flow function primitives are used in several flow structures. 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 the link to an objective by means-goal functions.

**Fig. 3.** MFM modeling example of 3 tank system. Being an experimental setup, the process is not assigned any objectives.
2. CHRONOLOGY OF MFM BASED APPROACHES TO OPERATOR SUPPORT

This section focuses on works that directly apply the MFM representation for different aspects of operator support. Approaches such as the diagnosis based on a functional Hazop (Hu et al., 2015), are closely related to the issues of operator support, but do not use the MFM model in an online fashion.

The fundamentals for using MFM in an automatic support system were established by Lind (1991) with the first implementation of generic reasoning in an object-oriented structure of MFM concepts. The ABSTRACTIONS framework made it possible to dynamically reason about the propagation of faults through a MFM model based on a generic rule base that could be applied to any given model and fault situation (Lind, 1991). Fang and Lind (1995) present a real time application of the ABSTRACTIONS framework through an interface to the programmable logic controller (PLC) of a pilot process that provides a causal diagnosis by propagating faults along the relations inside the MFM model.

In contrast, Sassen et al. (1991) proposed an efficient hierarchical search inference of possible root causes. The inference uses a reduction of the MFM model to a hierarchy of goals and sub-goals essentially reflecting a fault tree. The fulfillment of each of these goals can be evaluated against the actual state of the plant and causes can be traced deeper in the hierarchy until the root cause is identified. In the same manner local faults, which do not affect the plant as a whole, can be analysed by searching the respective sub-tree. Similar to this goal decomposition and the hierarchical search through the goals of the system, Takizawa and Monta (1996) introduce a hierarchical search in MFM models. An efficient diagnosis within the MFM model is realised by first tracing the fault to a specific flow structure in the hierarchy. The inferred fault propagation within the flow structures can be evaluated against the actual system state. Inconsistencies between the inference and measured deviations are used to identify the location of anomalies. They further presented heuristics to estimate measurements for components without instrumentation to establish more detailed diagnoses.

The application of an MFM based expert system for alarm based root cause analysis and sensor validation was demonstrated by Larsson (1996). The system is applied to group alarms according to the causality represented in MFM. The alarms are determined to be primary alarms close to the root cause of the disturbance or consequential alarms which are caused by a disturbance represented by another alarm. The evaluation of the state is proposed as interactive questions to the operator. However, these interactions slow down the system and impede the real-time applicability. Hence, the system is suggested to be used in an on demand manner to understand occurring situations. Taking into account that alarms are not necessarily configured correctly, Dahlstrand (1998) proposed a fuzzy assignment of the fault states before performing the alarm analysis described by Larsson (1996). This analysis was reported to yield more robust results that can cope with common issues like chattering alarms.

While the MFM modeling of goals and functions had been well established, Petersen (2000) identified a need to refine the representation of causality between flow functions. The distinction between direct and indirect influence and a comprehensive set of propagation rules for patterns in the MFM syntax are defined by Petersen (2000). Larsson et al. (2004) advocated for dynamic adjustment of causality in MFM models rooted in the consideration that the process dynamics are adjusted for different operation modes. The proposed method determines a pairwise correlation measure of local features in the process data. A low correlation measure indicates that the causal connection of the respective functions should be inhibited. Thus, the same model can be applied to the diagnosis of a process in different stages, given that the differences between operation modes only affect the causality and not the structural link of functions to components. (Larsson et al., 2004)

Dahlstrand (2002) expanded on the causal alarm analysis to identify minimal sets of root causes that fit the observed alarms. The analysis is done by reduction of causal dependency graph covering all function and state combinations in a given MFM model. The resulting causal paths can be covered as well as unobserved alarms making the method robust against chattering alarms. The method produces a number of explanations that can help narrow the operator’s focus to the correct process regions. Ouyang et al. (2005) demonstrated the application of MFM for the diagnosis of design accidents in a nuclear reactor.

Gofuku and Tanaka (1997) propose to augment the functional model with operational knowledge to include alternative behaviours of specific parts of the system. They realise this extension by generating a quantitative simulation model using Hybrid Phenomena Theory based on the abstraction in MFM to facilitate prognostic operator support. Furthermore, they propose an operator support interface utilising the design intention incorporated in MFM models to explain abnormal situations and augmented by mitigating actions. These possible counter-actions could be identified from the operational knowledge and verified by the quantitative simulation model. Expanding on their previous work, Gofuku (2011) demonstrated the use of additional knowledge in combination with the causal reasoning in MFM to generate linguistic explanations of an analysis in the model. They also reiterate a simplification method for the model previously outlined by Fang (1994). The simplification contracts functions that are not directly linked to components and thus reduces the paths included in the explanation for the operator.

Incorporating similar information to operational knowledge proposed in (Gofuku and Tanaka, 1997), Us et al. (2011) suggest an alarm design method based on MFM. External conditions and disturbances for individual functions of the system are used to identify points of mitigation and early warnings for arising alarms, creating a dependency structure of possible faults. The proposed alarm system considers only alarms associated with the modelled function of the plant and incorporates the consequence reasoning to predict alarms that will soon be triggered due to the propagation through the plant. (Us et al., 2011)

Zhang (2015) has presented the most recent set of propagation rules for MFM models and applied it to the di-
agnosis of a nuclear power plant. The work also explores the adaptation of the model or its links to the process to accommodate different modes of operation as previously pointed out by Larsson et al. (2004). In contrast to Larsson’s approach, the mode adaptation of process-function and means-ends relations is proposed rather than causalities inside the repetitive flows.

Finally, Wang and Yang (2016) outline an implementation of an MFM based expert system similar to Dahlstrands reduction of a causal dependency graph. However, they additionally include a link between modelled faults and common operator mistakes to represent the identified set of root causes in a more natural language than the underlying MFM model.

3. ONGOING RESEARCH

As outlined in Section 1 the operator tasks can be split up into the four parts: data acquisition, situation analysis, decision and counter-action execution. Some work has been published concerning the data acquisition and linking it to the causal analysis, e.g. (Dahlstrand, 1998) and (Larsson et al., 2004), but in general most of the work related to MFM considers the input to be valid alarms. Instead, the majority of applications of MFM focus on the second step of situation analysis. Most notably the groups of Lind and Larsson have proposed methods of cause analysis and more recently Wang and Yang (2016) have outlined an online system using MFM to identify root causes. The recent work of the group of Gofuku has been focused on using MFM as the basis for generating operation procedures. Either in unknown situations or to automate the generation of procedures the methods outlined by Gofuku (2011) can guide the execution of mitigation procedures once a diagnosis is established. While all of the research outlined above contributes to the different aspects of control room automation, each aspect has been researched mostly in isolation. Fig. 5 outlines the envisioned process for implementing a comprehensive operator support system.

To get meaningful results from the proposed knowledge based system the initial knowledge needs to be accurate. Nielsen et al. (2018) are proposing a framework for model validation by comparing the inference generated from an MFM model with the propagation documented by experts in e.g. a Hazard and Operability Study (HAZOP) or acquired from numerical simulation or process data. As outlined by Lind (2017), the creation of a model library will facilitate the modeling process. A library for different processes in the oil and gas sector is currently being developed at the Technical University of Denmark (DTU). By providing validated models for common subsystems in engineering documents of a specific application domain the overall model consistency can be improved.

In the control room the support system has to diagnose the situation and provide suggestions within a time frame of minutes or below to enable the operator to react before the system trips. In (Kirchhübel et al., 2017b), the authors outline a new propagation method that reduces the computational effort for the graph based inference of multiple concurrent offsets. The accuracy of the model can be further increased by the extension of the inference rules to include diverse implementations of control loops under investigation by Zhang and Lind (2017). To overcome the uncertainties introduced by heterogeneous alarm configu-
ration, the detection of faults by data analysis methods and machine learning are considered as interface between the process and the operator support system.

While a set of actual root causes can help focus the diagnosis, the estimation of tentative consequences and the ensuing risk is just as relevant to prioritise further steps and take appropriate actions. The operator can be provided with a range of plausible explanations for the situation based on the inference. The authors suggested a preliminary ranking method of identified root causes to determine the most relevant causes for the operator to consider (Kirchhübel et al., 2017b). In continuation of the considerations in (Zhang, 2015) the adaptation of the model used for the inference to the current situation is further being investigated in terms of knowledge representation (Kirchhübel et al., 2017a) and the identification of the current situation. Future research will further concern the loop closure from actually observed situations and operator reactions to the underlying model.

As the final stage of the operator support system the knowledge represented in an MFM model can be used for automatic planning of procedures to mitigate a detected deviation. Based on the concepts proposed in (Gofuku, 2011), Song and Gofuku (2017) outlined a planning method using the MFM based causal inference. This branch of investigation is also pursued by the group at DTU.

4. CONCLUSION

The presented chronology shows that a number of implementations and applications have been reported continuously since the first implementation of MFM. However, the complementary elements of alarm management and root cause analysis and reaction suggestions have been widely separated in the research. The current research efforts at the Technical University of Denmark and collaboration partners aim to combine the whole range from initial offset detection to alarming and finally counter-action generation. Within the context of operator support the integration of diverse methods with knowledge representation in MFM are under investigation. The current research projects and partners as well as recent publications can be found on the research group’s website http://mfm.elektro.dtu.dk.

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