On-Line Root Cause Analysis For Nuclear Power Plant Control Rooms

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Abstract: *This paper describes a new technology for analyzing alarm cascades in nuclear power plant control rooms in real-time, thereby making operation safer and more productive. The technology is based on multilevel flow models and a root cause analysis algorithm developed at Lund University and GoalArt. It enables the solution of the alarm cascade problem for full-scale nuclear power plants. In the next few years, we hope to introduce this technology as a technically mature functionality in control rooms for complex systems.*

Keywords: Alarm cascades, multilevel flow models, root cause analysis.

1. INTRODUCTION

In complex technical systems, a fault usually leads to several consequential faults. Most or all of these consequential faults lead to fault indications, (alarms and events). Normally, alarms arrive out of time order, depending on system physics, alarm limit settings, and time stamping, and it is often impossible for operators to analyze the developing fault situation. Instead, they must alleviate the situation with more general means, and will not have full knowledge of the real fault until later, [1, 4].

This effect is known as alarm cascades, alarm showers, or alarm floods. It is the most difficult alarm problem to handle and also the most dangerous one, since it appears in exactly those situations where the alarm system is needed the most. So far, no viable solution to this problem has been available, [9, 21].

Methods based on multilevel flow models (MFM) have been developed at the Danish Technical University, Lund University, Stanford University, and at the company GoalArt. These methods use simple models of goals and functions to capture the causality of technical systems. An algorithm based on MFM has been developed, and this algorithm offers a complete and efficient solution to root cause analysis of technical systems.

The MFM-based algorithm can handle all possible combinations of faults, including multiple independent root faults and circular causations in a theoretically correct and complete way. Thus, it makes no single fault assumption.

The algorithm is linear in target system size, for execution time and memory demands, and also very fast. A complete worst-case analysis of 500 – 1 000 incoming events takes less than a second on a standard PC. Thus, it is possible to analyze large alarm cascades in real-time, while they develop.

Finally, the modeling effort is much less than with other knowledge-based methods. A nuclear model of the Forsmark 3 nuclear power plant / Hambo simulator, comprising 6 500 alarms and events, was built in about *four man-months.*

This method offers the possibility of solving the problem of large alarm cascades. We believe that this will be one step towards enabling nuclear control room personnel to analyze and understand the fault situations that precede smaller and larger incidents.

MULTILEVEL FLOW MODELS

The root cause analysis algorithm is based on a modeling methodology called Multilevel Flow Models (MFM). These are graphical models of goals and functions of technical systems. The goals describe the purposes of a system or subsystem, and the functions describe the capabilities of the system in terms of flows of mass, energy, and information. MFM also describes the relations between the goals and the functions that achieve those goals, and between functions and the sub-goals.

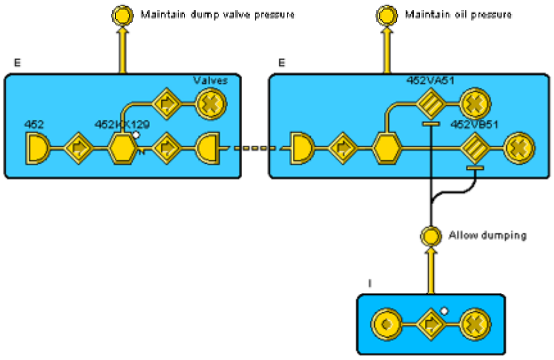


Figure 1. An excerpt of the Forsmark 3 MFM model, showing a small part of the valve system for steam by-pass.

MFM was invented by Morten Lind at the Technical University of Denmark, [18-20]. Several new algorithms and implementations have been contributed by Jan Eric Larsson at Lund Institute of Technology, [2, 12-15, 28], and more lately, GoalArt. Other important contributions include [5, 6]. MFM development started in the late seventies and has reached industrial application in the beginning of this century, [16, 17, 27]. MFM provides a good basis for diagnostic algorithms.

The details of MFM have been described an several previous publications, [12-14]. A small model fragment from the Forsmark 3 nuclear model is shown in Figure 1. Note that there are small but interesting variations between the MFM "dialects" used in Denmark, Sweden, and Japan.

ADVANTAGES OF MFM

The algorithms described in [12-14] are based on discrete logic. The MFM algorithms all operate by searching in fixed graphs. All cases are handled by search methods of linear or sub-linear complexity. Together with the discrete logic, explicit means-end concepts, and graphical nature of MFM, this gives several advantages:

- The graphical representation provides strong support for knowledge base overview and consistency.
- The high level of abstraction makes knowledge acquisition, knowledge engineering, and knowledge base validation and support considerably easier than with standard rule-based systems or fuzzy logic systems.
- The graphical nature of the models allows the algorithms to have good real-time properties, such as an easily computed worst-case time, low memory demands, and high efficiency.
- The high level of abstraction allows the algorithms to be very fast. A worst-case alarm analysis on the full Hambo system takes less than a second on a standard PC.

These advantages have been observed in practice, during two nuclear projects, [16, 17, 27].

ROOT CAUSE ANALYSIS

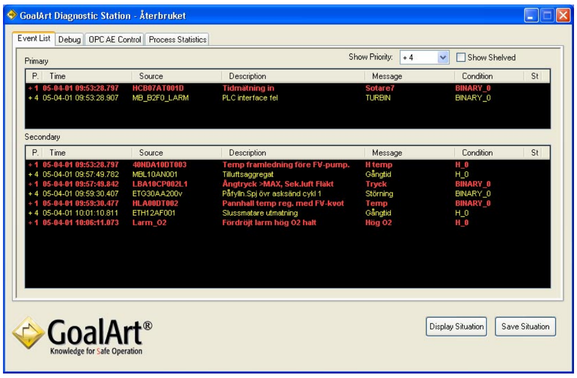
A fault in a plant usually leads to several consequential faults. When the plant is well equipped with alarms, this causes a large number of alarms. A single fault may lead to hundreds of alarms, a so-called *alarm cascade.* Quite often, the root alarm does not appear first, and alarm cascade situations can be very difficult to analyze.

GoalArt's algorithm for root cause analysis analyzes complex alarm situations and separates root causes from consequential faults. The root causes can be shown in a separate alarm list, while the consequential faults are shown in another list or are suppressed and presented when needed, see Figure 2.

AM ONGOING NUCLEAR PROJECT

A GoalArt pilot system has been integrated with the Hambo simulator at Hammlab, Institute for Energy Research (IFE) in Halden, Norway, [16, 17, 27]. During the remainder of the project, we will perform operator testing with crews from the Scandinavian nuclear plants. The project is sponsored by all Scandinavian nuclear power plants together.

We have already seen indications that this new technology means a *revival of the alarm list.* With our system, the primary list contains the 1-5 originating alarms only, and this list is useful at all time instants during an incident. The alarm list guides the operator to an immediate understanding of the fault situation, and works as a checklist of which faults that remain to take care of. Instead of being ignored, the alarm list becomes a primary source of information to the operator during complicated and critical situations.



Show Priority: + 4 □ Show Shelved

Primary

P.	Time	Source	Description	Message	Condition	St
+ 1	05-04-01 09:53:28.797	HCB07AT001D	Tidmätning in	Sotare7	BINARY_0	
+ 4	05-04-01 09:53:28.907	MB_B2F0_LARM	PLC interface fel	TURBIN	BINARY_0	

Secondary

P.	Time	Source	Description	Message	Condition	St
+ 1	05-04-01 09:53:28.797	40NDA10DT003	Temp framledning före FV-pump.	H temp	H_0	
+ 4	05-04-01 09:57:49.782	MBL10AN001	Tilluftsaggregat	Gångtid	H_0	
+ 1	05-04-01 09:57:49.842	LBA10CP002L1	Ångtryck >MAX, Sek.luft Fläkt	Tryck	BINARY_0	
+ 4	05-04-01 09:59:30.407	ETG30AA200v	Påfylln.Spj övr asksänd cykl 1	Störning	BINARY_0	
+ 1	05-04-01 09:59:30.477	HLA00DT002	Pannhall temp reg. med FV-kvot	Temp	BINARY_0	
+ 4	05-04-01 10:01:10.811	ETH12AF001	Slussmatare utmatning	Gångtid	H_0	
+ 1	05-04-01 10:06:11.073	Larm_O2	Fördröjt larm hög O2 halt	Hög O2	H_0	

Figure 2. A screen shot from a GoalArt Diagnostic Station, showing a (simulated) situation with two independent root cause alarms, and several consequences. Root causes are shown in the upper list, consequences in the lower one. The coloring indicates dynamic priority set by another algorithm.

The HAMBO simulator is an experimental simulator located at IFE in Halden, Norway, and the simulator is used for performing human performance experiments, as well as testing of operator interfaces, alarm systems, and other operator support systems. The simulator's reference plant is the Forsmark 3 nuclear power plant in Sweden. Within the project, we have covered around 6 500 status signals, which is a major part of the simulator, using both MFM-based root cause analysis and state-based alarm priority. The project also includes development and testing of new ways of alarm presentation, using the extra information available from the root cause analysis and state estimation. Concerning the existing alarm system of HAMBO, see [10, 25].

The aim of the alarm project has been to reach a full integration of the alarm analysis and state-based alarm priority in the HAMBO simulator, so that the new algorithms could be tested under realistic circumstances on-line with real operator crews. In this way, we hope to be able to obtain measures of the usefulness and efficiency of the alarm reduction and situation assessment provided by the GoalArt alarm algorithms.

MODELING EXPERIENCES

During the nuclear project, we have gained a large amount of practical modeling experiences using MFM. We believe that the Forsmark 3 model is by far the largest hand-made MFM model in existence. It was built during the second half of 2005 and first half of 2006 using an estimated total number of 4 man-months, or 700 man-hours. The model contains some 6 500 input signals, which means that the speed of modeling was an average of almost 10 signals per hour. The modeling was performed by three knowledge engineers, with one of them handling some 75 - 80 % of the total modeling effort.

One important lesson learnt is to base the modeling strongly on available input signals. In the first pilot, we tried to build general, reusable MFM models, and only then adding the input signal information, in a “two-step” fashion. This lead to a pilot system with some 300 inputs, which was built in 1.5 man-months.

In the larger, full-scale implementation, we changed our approach and focused on the list of input signals, building minimal MFM models around each set of signals. This lead to a large increase in modeling efficiency, and the 6 500-signal system was built in some 4 man-months. In fact, the resulting models also became better adapted to reuse.

Thus, one important lesson is that MFM modeling gains by trying to build *small models,* rather than building general models. The MFM language itself will provide a structure that makes any model fairly well adapted to reuse, so any generalization beyond the scope of available inputs is likely to be a waste of time and resources.

In general, we have seen that MFM modeling tends to be quite efficient, mainly because of the following factors:

- The means-end information needed is easy to grasp and quite simple, compared to all the detailed and complex properties of the underlying technical system.
- The MFM structure lends itself to extensive “code” reuse, and the hierarchical structure makes it very easy to build the models in a top-down fashion.
- Even a complex system like a nuclear power plant contains relatively few flow constructions, and most of these are trivial in detail. More than 90 % of the systems can be modeled “on routine,” without any specific problem solving.

We have seen that MFM allows for a *massive reuse of model solutions.* Several sub-systems of the first, smaller pilot were immediately useful in the full-scale project, and demanded minimal changes.

The built-in abstraction property of MFM is a valuable asset in itself. It allows for a top-down modeling approach, but it also allows for an easy way of building simplified models of processes with fewer input signals.

In a recent GoalArt project, the author built an MFM model of the mesa burner of a Swedish pulp and paper plant, which suffered an infamous alarm-related explosion in 1998. The model comprises around 500 input signals, and was built in less than two workdays, and tested and validated in another two days. This translates to a modeling speed of more than 30 inputs per hour.

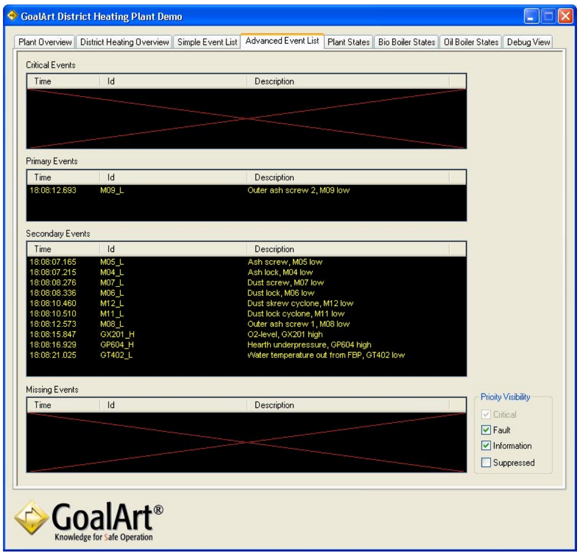
We envision that smaller MFM models of nuclear power plants, for example, comprising the 100 – 150 most important safety parameters only, could be built with a similar effort.

The pulp and paper model correctly analyses the alarm cascade that preceded and caused the 1998 explosion. If the mill had had a GoalArt system, they would have had more than 10 minutes to empty the boiler and avoid the explosion. In reality, the operators were unable to understand the fault situation and took no action to avoid the accident.

HUMAN-MACHINE INTERFACE

One critical aspect of an alarm system is the *presentation* of the alarms. The alarm list is far from ideal. It dates back from the line printer times, and is designed as much for documentation as for real-time use. We strongly believe that the best presentation strategy is to combine classical alarm lists with alarm presentation in process schematics.

The list presentation can easily be improved using GoalArt’s algorithms for state-based alarm priority and root cause analysis. Our current standard solution is to use several lists, see Figure 3.



Critical Events

Time	Id	Description

Primary Events

Time	Id	Description
18:08:12.693	M09_L	Outer ash screw 2, M09 low

Secondary Events

Time	Id	Description
18:08:07.165	M05_L	Ash screw, M05 low
18:08:07.215	M04_L	Ash lock, M04 low
18:08:08.276	M07_L	Dust screw, M07 low
18:08:08.336	M06_L	Dust lock, M06 low
18:08:10.460	M12_L	Dust skrew cyclone, M12 low
18:08:10.510	M11_L	Dust lock cyclone, M11 low
18:08:12.573	M08_L	Outer ash screw 1, M08 low
18:08:15.847	GX201_H	O2-level, GX201 high
18:08:16.929	GP604_H	Hearth underpressure, GP604 high
18:08:21.025	GT402_L	Water temperature out from FBP, GT402 low

Missing Events

Time	Id	Description

Prioity Visibility
☑ Critical
☑ Fault
☑ Information
☐ Suppressed

Figure 3. A screen shot of GoalArt’s improved alarm presentation, with separate lists for critical priority alarms, root cause alarms, consequential alarms, and missing alarms.

In our presentation, we separate root cause alarms and present them in a special list, while all consequences are shown in another list. This gives the operator an idea of the number of independent root causes at a glance. For example, in Figure 3, there is a single root cause, while in Figure 2 there are two independent fault chains.

In addition to the root cause analysis, our system assigns a dynamic priority to every alarm. If an alarm has the highest priority (critical), we show it in the top list of critical alarms, independent of whether it is a root cause or a consequence. For example, we recommend giving all major trip signals a critical priority. In this way, a scram signal will appear in the critical list, while the cause of the scram will appear in the root cause list. All 300 – 500 consequence alarms that normally appear during a scram will be shown in the consequential list.

Finally, our system also knows what alarms to expect in different states, and can calculate so-called missing alarms. These are messages saying that an alarm should have come (and might have been suppressed) but did not. These missing alarm messages are shown in a fourth list, see Figure 3.

In this way, if something goes wrong during, say, a scram operation, and some system fails to work, the operator will see the missing actions at a glance.

ALGORITHM EFFICIENCY

The details of the MFM-based root cause analysis have been given a more formal description in [12-14]. A number of additional features have been developed by GoalArt, whereof several are proprietary. The algorithm has been industrially proven in several applications, in conventional and nuclear power, for medical and chemical systems, power grids, and for electrical and control systems in vehicles. It has a number of interesting properties, which make it well suited for realistic size diagnostic problems.

- It provides a single, correct analysis of every possible combinations of inputs allowed by MFM. This property was not present in the published versions, but has been developed by GoalArt in later years.
- It updates its diagnosis incrementally with every new incoming data, which allows it handle interventions, which manifest themselves in changing input data. However, it is sensitive to interventions, which mean that the modeling assumptions are no longer, valid, [22].
- The root cause analysis algorithm is independent of timing information. Thus, it handles situations where faults arrive in out-of-time order.
- If the MFM model gives a correct description of the causality of the target system, the algorithm will give the correct result, and we contend that there is no way of computing a “more correct” result, given the limitations to the type of systems that the MFM language can describe.
- The algorithm is efficient and it is possible to calculate worst-case time and memory demands.
- The size of an MFM model grows linearly with target system size, and the time and space demands of the algorithm grows linearly or less than linearly with MFM model size.

The alternative to MFM-based root cause analysis is to use fault trees or rule-based expert systems. The effort of using one of these techniques is order of magnitudes higher than with MFM, and often prohibitive.

OTHER MFM ALGORITHMS

Based on the MFM technology, GoalArt has developed several algorithms that can perform diagnostic reasoning tasks, for use either during plant design and redesign, or on-line during actual operation.

- Sensor placement analysis uses an MFM model to calculate whether a certain set of sensors can detect all faults in a process, and if not, where the blind spots are. This can be used to validate that all faults can be detected by the alarm system, to validate that a certain sensor is indeed superfluous and can be removed, and to validate sensor redundancy in a formal way.
- Probability and safety analysis (PSA) uses an MFM model and pre-calculated or measured values of reliability and availability to calculate reliability values for an entire sub-system or plant. It automatically obtains reliability and availability values for the plant, and checks that all systems fulfill SIL value demands. The algorithm follows the method described in the IEC 61508 standard and can be used off-line during design, and on-line during operation.
- Single-fault tolerance analysis uses an MFM model to validate that any single fault cannot cause a stop of the entire plant. Alternatively, the algorithm can be set up to validate that a design fulfills N-way redundancy for all involved systems.

All these design and validation algorithms share the formal property that, if the MFM model is correct, the validation can be proved to be correct.

- Sensor fault detection uses an MFM model and incoming alarms and events to validate that the alarms are consistent, that is, to detect erroneous measurements, alarm limits, and alarm indications.
- Failure mode analysis uses an MFM model to predict consequences of the current fault situation, as well as of proposed actions taken by the operator. This resembles FMEA, but can be used on-line as a real-time planning support tool.
- Startup planning and ready-to-run validation uses an MFM model to either plan a complex startup procedure, or to validate that each step in a maneuver is allowed. For example, it can be used to check that support systems and activated before operations are commenced.

All these algorithms use the same MFM model as a database. Once a model has been built, all algorithms are available at no further modeling cost.

STATE OF THE ART OF DIAGNOSIS

Complex fault situations or alarm cascades are a well-known problem in nuclear control rooms, but there is currently little support available for diagnosis of such situations:

- Some methods offer the possibility of suppressing consequential events in a rule-based fashion, where the rules are created manually, for example fault trees and rule-based expert systems. Such solutions try to lessen the number of incoming events, but they are difficult to maintain for large systems.
- Some tools allow the construction of graphical models of components and topology, but rules of code must still be written and added to the objects.
- Tools used for root cause analysis on the Internet utilize statistical correlation techniques to automatically learn common fault situations and replace an alarm shower with a single event indication. However, these methods do not solve the problem, because they still cannot identify the root cause of an alarm shower, the learning takes time, and the methods are unpredictable when faced with new topology and/or new, unexpected fault situations, which are the most important situations to handle correctly.
- There is a long tradition of model-based fault diagnosis in testing of electronic circuits, [8, 23]. These methods use qualitative physics based on Reiter's algorithm, [7, 24]. These methods differ substantially in that they assume the possibility of using test inputs and are geared towards testing of discrete logic systems. Other fairly similar contributions are described in [3, 26]. These methods are still on the research level and need extensive computing power even for small systems, see [11] for a specific analysis and contribution to the computational speed problem.

Currently, most nuclear control rooms do not use knowledge-based operator support systems in their daily operations.

Fuller and more comprehensive comparison between the MFM-based approach and other approaches to model-based diagnosis are found in [12] and especially in [14]. These comparisons have been well corroborated by later results produced at GoalArt.

CONCLUSIONS

This paper gives an overview of new methods for solving alarm problems. In particular, we have described new methods for reducing alarm cascades to single root cause alarms. This can be done without permanently removing alarms from the system. In fact, with GoalArt's methods in place, the new availability of large amounts of alarm information can be used without the risk of information overload.

The aim of the ongoing alarm project is to reach a full integration of the alarm analysis and state-based alarm priority in the HAMBO simulator, so that the new algorithms can be tested under realistic circumstances on-line with real operator crews. In this way, one will be able to obtain measures of the usefulness and efficiency of the alarm reduction and situation assessment provided by the specific alarm algorithms.

The operator testing will take place mainly during the spring of 2007. However, we have already seen from early demonstrations, that our system can help to revive the alarm list, making it a dynamically available tool for monitoring and diagnosis, while incidents develop. We have good hopes that the operator testing will corroborate these early indications. If so, the alarm list will turn into a useful tool in complex and critical fault situations.

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